

**THERMAL CONDUCTIVITY OF
SEDIMENTARY ROCKS -
SELECTED METHODOLOGICAL,
MINERALOGICAL AND TEXTURAL STUDIES.**

by
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SUMMARY.

The thermal conductivity of sedimentary rocks is an important parameter in basin modelling as the main parameter controlling the temperature within a sedimentary basin. Measured thermal conductivities, mainly on clay- and mudstones, are presented in this work. The measured values are compared with values obtained by using thermal conductivity models. Based on our measurements some new thermal conductivity models are developed. The main findings of this study can be summarised as follows:

Measured thermal conductivities.

- Thermal conductivities presented in this thesis are lower than most previously published data. Divided bar measurements on four selected clay- and mudstones from England were in the range of 0.66 W/m-K to 0.97 W/m-K. For three of these clays, the measurements were less than half of the values previously published for the same clays.
- In a study of unconsolidated sediments, a constant deviation of about 0.15 W/m-K was found between thermal conductivities measured with a needle probe and a divided bar apparatus. A similar disagreement between these two methods is also previously reported.

Modelling thermal conductivities.

- Accepted thermal conductivity models based on the geometric mean model, where matrix conductivity is estimated from mineralogy, fail to predict the thermal conductivity of clay- and mudstones.
- Despite this, models based on the geometric mean model, where the effect of porosity is taken account of by the geometric mean equation, seem to be the best.
- For clay- and mudstones the textural influence on thermal conductivity is underestimated by existing models. This influence is considered to be the main reason for the unrealistic results with the mineralogically based models.
- The grain size was found to influence thermal conductivity for artificial quartz samples. This effect seems to be logarithmic with highest effect for the fine grained samples.
- The clay mineral content seems to be a point of uncertainty in both measuring and modelling thermal conductivities.
- In order to develop a good universal thermal conductivity model it is necessary to include many mineralogical and textural factors. As this is difficult, different models restricted to specific sediment types and textures are suggested to be the best solution to obtain realistic estimates applicable in basin modelling.

PREFACE.

This thesis constitute the research project *Shale and Claystones. Physical and Mineralogical Parameters in Basin Modelling*. This has been a part of the joint project *Clay, Claystone and Shale Problems in Petroleum Geology* a co-operation between the Department of Geology and Resources Engineering, NTNU and the Department of Geology, University of Oslo.

What is the thermal conductivity of sedimentary rock? The most honest answer is still: «I do not know.» When starting on this project the thermal conductivity was assumed to be one of many parameters which would be touched on. Today, I am still studying this physical parameter called thermal conductivity, and through these six years of thesis work I realise that a lot of work remains to obtain a satisfactory understanding of this parameter. In approaching an answer to the key question much attention has been paid to why we do not know the thermal conductivity of sedimentary rocks better. A conclusion is unfortunately that the thermal conductivity is not only influenced by the porosity, texture and mineralogy but also by whom and how the measurements are carried out.

I would leave it to the readers and the dr.ing committee to evaluate the scientific contribution of this work. My personal evaluation of this thesis period is that I have gone through some valuable years where I have gained some insight in and respect for scientific methodology. I have also in this period established a valuable network of contacts which has been both useful and pleasant and which I hope is sustainable. Although this period of continuing education have been instructive, it has certainly not been without times of adversity.

ACKNOWLEDGEMENTS.

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I am indebted to the following people for their contributions in the process which resulted in this thesis:

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- Arne Hov, Karl Isachsen, Arild Monsøy, Ingrid Vokes and Ivar Rømme for technical support in the laboratory work.
- Anne Irene Johannessen for drawing many of the figures.

Thanks are also expressed to friends and colleagues at the Department of Geology and Mineral Resources Engineering, NTNU for encouragement and help with all kinds of emerging problems. Finally I would honour my mother who encouraged me, but died during this period. As a good example I realise that she will influence choices I have to make also in the future.

Trondheim, October 1997.

Kirsti Midttømme
Kirsti Midttømme

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Paper 6. Sensitivity of thermal conductivity for temperature history of sedimentary basins: a case study from the northern North Sea.	16 pp.

When considering the thesis as a whole it consists of three parts, a summary (Paper 1), a section on thermal conductivity measurements and modelling (Papers 2-5) and a section on the application of thermal conductivity models in basin modelling (Paper 6).

LIST OF PAPERS.

Paper 1. Thermal conductivity of sedimentary rocks - uncertainties in measuring and modelling.

Kirsti Midttømme & Elen Roaldset.

- In manuscript.
- Submitted to *Mudrocks at the Basin Scale: Properties, Controls and Behaviour. Geological Society Special Publications.*
- Part of the paper entitled «Uncertainties in determination of thermal conductivity of clay- and mudstones» was presented as a poster at *Mudrocks at the Basin Scale: Properties, Controls and Behaviour. The Geological Society Meeting, London, January 1997.*

Paper 2. Thermal conductivities of argillaceous sediments.

Kirsti Midttømme, Elen Roaldset & Per Aagaard.

- In: D.M. McCann, M. Eddleston, P.J. Fenning & G.M. Reeves (eds.). *Modern Geophysics in Engineering Geology. Geological Society Engineering Geology Special Publication, 12, 355-363.*

Paper 3. Thermal conductivity of selected clay- and mudstones from England.

Kirsti Midttømme, Elen Roaldset & Per Aagaard.

- In press. *Clay Minerals*, 33, 131-145.
- Presented at *The Rosenqvist Symposium on Clay Minerals in Modern Society, Oslo, May 1996.*

Paper 4. *Thermal conductivity of unconsolidated sediments from the Vøring Basin, Norwegian Sea.*

Kirsti Midttømme, Joar Sættem & Elen Roaldset.

- In press. In: M.F. Middleton (ed.). *Nordic Petroleum Technology Series: Two*, Nordisk energiforskningssamarbejde, 1997.

- Part of the paper was presented and is published as abstracts in:

EAGE 57th Conference, Extended Abstracts Volume 2, F004 Glasgow, May 1995, ISBN 90-73781-06.

2nd Nordic Symposium on Petrophysics and Reservoir Modelling, Conference Volume, January 1996, 85-87.

Paper 5. *The effect of grain size on thermal conductivity of quartz sands and silts.*

Kirsti Midttømme & Elen Roaldset.

- In press. *Petroleum Geoscience*.

- The paper was presented at *30th International Geological Congress, Abstracts Volume 1 of 3*, H-2-29 04855 3702, pp 352, Beijing China, August 1996.

Paper 6. *Sensitivity of thermal conductivity for temperature history of sedimentary basins: a case study from the northern North Sea.*

Kirsti Midttømme & Willy Fjeldskaar.

- In manuscript.

- The paper will be presented at *23. Nordiske Geologiske Vintermøde*, Århus, January 1998.

INTRODUCTION.

GENERAL REMARKS.

Temperature.

All physical and chemical processes in nature depend on temperature. To know the temperature is important in the understanding and the modelling of these processes. Equipment can be developed which easily and exactly measures the temperature. However, for basin modelling purposes, this equipment is useless and therefore the temperature in sedimentary basins cannot be satisfactorily measured. The temperature within the basins has to be estimated. The thermal conductivity of the sedimentary rocks filling the basin is a key parameter in these temperature models.

Basin modelling.

Basin modelling is a tool in the evaluation of the hydrocarbon potential of sedimentary basins. It is a young discipline within the broader subject of petroleum geology. The first integrated one-dimensional basin models were presented at the end of the 1970s. Since then a variety of basin modelling tools and techniques has been developed, including in recent years also three-dimensional models (e.g. Hagemann, 1993).

Using basin modelling programs, the processes taking place within sedimentary basins, such as heat and fluid flow, compaction, hydrocarbon generation, expulsion, secondary migration are modelled and the results of the processes integrated (e.g. Hermanrud, 1993). Still, the results of the modelling have to be considered with care because of the uncertainties and the inconsistencies in the models, the input data and the calibration parameters. Basin modelling is important as a tool to identify the sources of error in the modelling and the sensitivity of the parameters.

Why focus on the thermal conductivity?

The thermal conductivity is in itself of no interest in hydrocarbon generation or exploration. The interest in this parameter lies in its control of the temperature. Estimates of the temperature within sedimentary basins require modelling of the heat transfer through the basins. The main mechanism of heat transfer in sedimentary basins is by conduction. The principle of equilibrium underlies this heat mechanism. If a temperature gradient exists in a material, heat transfer would try to even out the temperature. The mechanism can physically be explained by transfer of energy from more energetic atoms and molecules to less energetic ones. A condition for conduction is contact between the particles.

The heat transfer due to conduction is expressed by Fourier's law (eq.1).

$$q = -k \frac{dT}{dz} \quad (\text{eq.1})$$

q	-	heat flux (W/m ²),
k	-	thermal conductivity (W/m·K),
dT/dz	-	temperature gradient.

The heat flux, q , is the heat transfer in the z direction per unit area perpendicular to the direction of transfer, and is proportional to the temperature gradient, dT/dz in this direction. The proportional constant, k is a transport property known as the thermal conductivity and is a characteristic of the sedimentary rock (Incropera & Witt, 1990).

Heat is also transferred by other mechanisms such as convection and radiation. In this study the heat contributions from these mechanisms are neglected. At temperatures lower than 250 °C heat transfer from radiation is insignificant, particularly in fine grained sediments (e.g. Johansen, 1975; Midttømme et al., 1994).

Whether there is a heat contribution from convection is more uncertain. The permeability is an important factor controlling convection. In this study I have mainly considered low permeable rocks where the contribution from convection is considered to be minimal compared to conduction (e.g. Ungerer et al., 1990). I have therefore considered to not take into account this contribution.

THESIS OUTLINE.

The thesis consists of six papers. Each paper represents a self contained work. When considering the thesis as a whole, it consists of three parts, a summary (Paper 1), several studies of thermal conductivity measurements and modelling (Papers 2-5), and a study of the application of the thermal conductivity models in basin modelling (Paper 6). A brief introduction and some comments to the papers follows:

Paper 1. Thermal conductivity of sedimentary rocks - uncertainties in measuring and modelling.

Paper 1 is a review of this thesis and a summary of the five following papers. Also some new statements and assumptions are presented. It might be seen as a confession of failure that this overview paper is entitled «uncertainties in measuring and modelling» and discusses why we do

not know the thermal conductivity of sedimentary rocks. The paper is based on 6 years of thermal conductivity studies and measurements with a divided bar apparatus carried out mainly on clays and mudstones. Not all statements particular to measuring of thermal conductivities are well examined or well-founded. By introducing these, I hope that further thermal conductivity studies can continue this work and confirm or deny these statements. The paper might suffer by the restriction of the length. Instead of a thorough discussion of some main factors of uncertainties we have tried to touch them all on a restricted number of pages.

Paper 2. Thermal conductivities of argillaceous sediments.

Paper 2 presents and discusses thermal conductivities measured on selected samples from the Norwegian Continental Shelf. For basin modelling purposes these samples have great importance. However, the quality of the samples from well A is a point of uncertainty in this study. These samples were prepared from side wall cores contaminated with barite, where the interpretation of the mineralogy and the determination of the direction due to the bedding were problematic. Another problem with the samples from well A, is, although to the naked eye seeing rather homogeneous, their very inhomogeneous nature (Figure 1 & 2). This paper might be marked by being my first written paper. If it had been written today, more attention would have been given to the textural factors of the samples. In relation to the following paper, this paper show trends in the measuring of thermal conductivity, which form the basis for ideas and statements further developed in the following papers.

Paper 3. Thermal conductivity of selected clay- and mudstones from England.

Thermal conductivities of four onshore clay- and mudstones from England are presented in Paper 3. The limited number of samples restricts the possibility to do statistical analyses of the thermal conductivity measurements and the laboratory data. The laboratory work carried out in this study is more comprehensive and thorough than those presented in the other papers in this thesis, with many parallel thermal conductivity measurements on each sample. A valuable part of this study is the comparison between the needle probe, the divided bar, Middleton's method, and those methods previously published by Bloomer (1981).

Paper 4. Thermal conductivity of unconsolidated sediments from the Vøring Basin, Norwegian Sea.

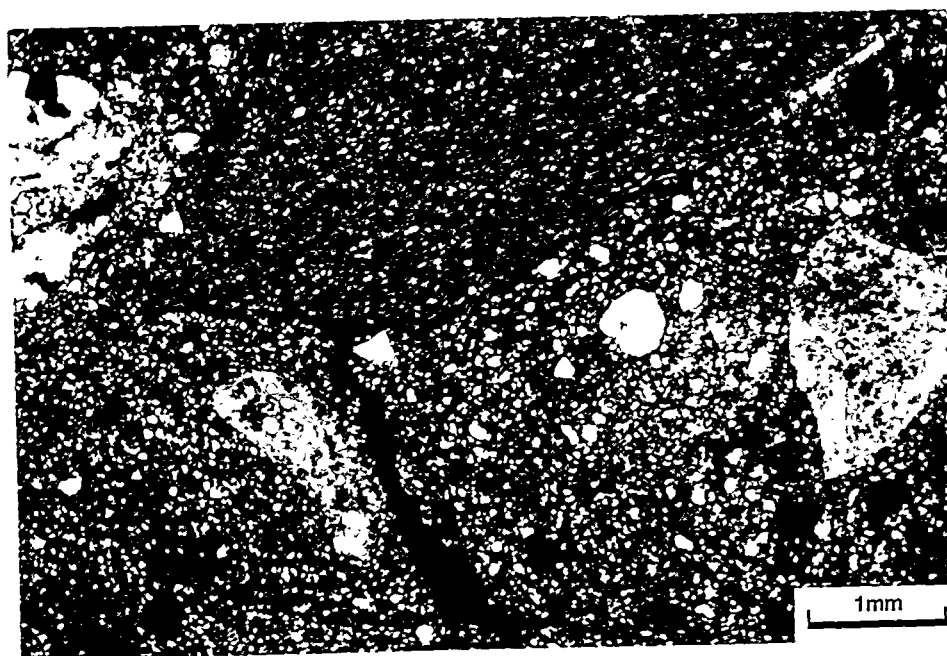
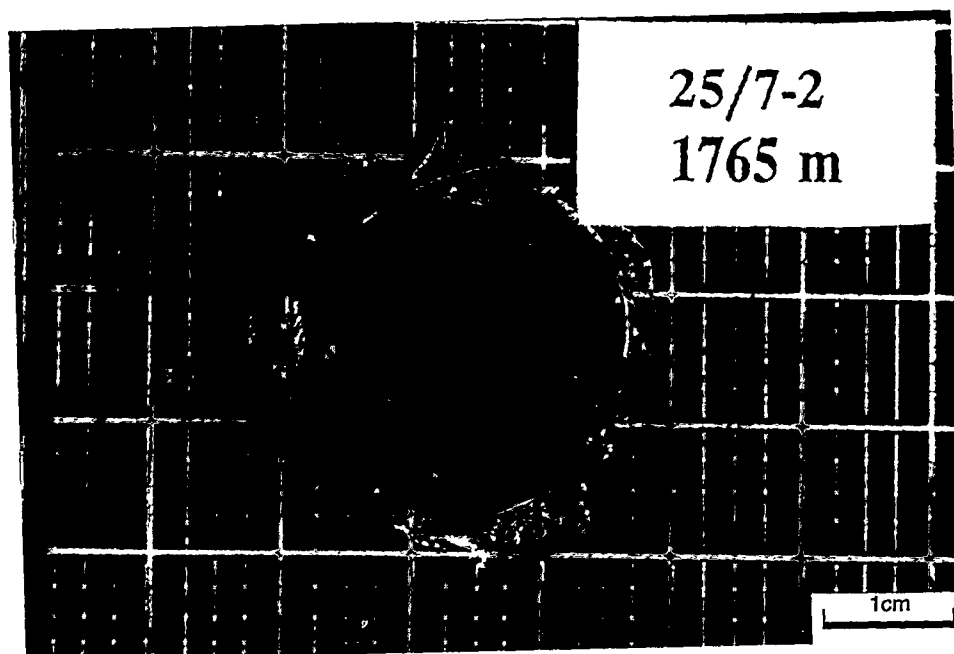
The most comprehensive study in this thesis is presented in Paper 4. The young marine sediments studied here were obtained by gravity coring. For basin modelling purposes these samples are of lower importance. The water content of these samples is extremely high compared to those observed in more consolidated rocks. I believe that the study of these unconsolidated sediments has given basic knowledge of heat transfer by conduction which also will give insight in this mechanism for more consolidated sediments. A weakness with this study might be that the samples are too homogenous. Comparative thermal conductivity measurements between needle probe method and the divided bar apparatus is also published in this paper. These measurements show a rather constant deviation, where the divided bar apparatus give systematically lower values than the needle probe method.

Paper 5. The effect of grain size on thermal conductivity of quartz sands and silts.

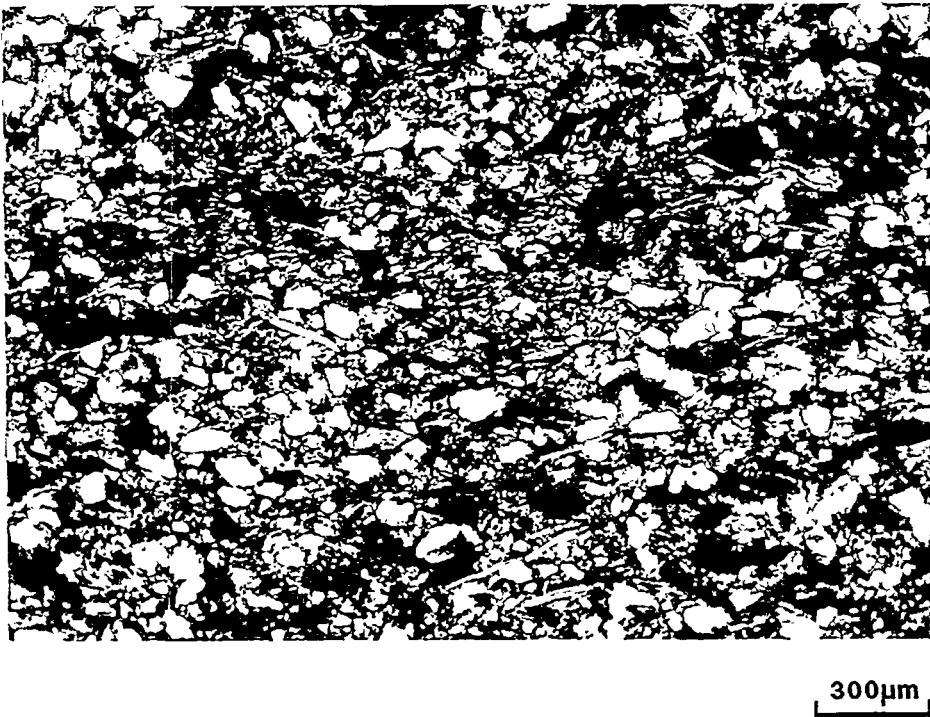
Paper 5 distinguishes itself from the other papers by treating artificial samples. By making the concession that natural samples are too complex to confirm a correlation between the grain size and the thermal conductivity, moulded samples from crushed quartz were used. For the water saturated samples a logarithmic correlation between the grain size and the measured thermal conductivities was found. The effect of pore size could possibly have been more emphasised in this study. Since the grain size is found to affect thermal conductivity, the pore size is assumed to have a corresponding effect.

Paper 6. Sensitivity to thermal conductivity for temperature history of sedimentary basins: a case study from the northern North Sea.

The object of Paper 6 is to show how the variation in estimated thermal conductivity effects the modelled temperature history of a sedimentary basin. This effect is exemplified by studying a section across the northern North Sea. Thermal conductivities are estimated by six different methods, and four comparative case studies of temperature histories are considered. Since the temperature history of this cross-section is unknown, the assessments of the different thermal conductivity models are only based on assumptions. Considerable variations in the estimated temperature histories is observed.



Figures 1 & 2. Sample A7 in Paper 2. The sample is from Middle Eocene. The side wall core (Figure 1) shows a dark grey mudstone. Drilling fluid contamination is seen as light spots on the surface. The thin section micrograph (Figure 2) shows a sandy mudstone with lithic fragments of light brown claystone, quartzite and carbonate.



Figures 3 & 4. Sample B3 in Paper 2 (Zhang et al., 1992). The sample is from Upper Jurassic Heather Formation. The core section (Figure 3) shows a mottled pattern. The bedding is modified by bioturbation. The thin section micrograph (Figure 4) shows silt-size quartz, feldspar and elongated mica minerals in a clayey matrix.

MEASUREMENTS OF THERMAL CONDUCTIVITIES.

Thermal conductivities reported in this study are mainly measured with a divided bar apparatus, developed at the Institute of Refrigeration, Norwegian University of Science and Technology (Brendeng & Frivik, 1974). The reproducibility of repeated measurements with this apparatus on a variety of rock samples is within 3.0 % (H. Johansen. pers. comm, 1992).

The measurements presented in this study were, except for some data in Paper 5, measured on water saturated samples. All measurements were carried out at atmospheric pressure and at temperatures in the range 15 - 55 °C. To prevent drying of the samples and reduce the effect of water movement, the temperature gradient across the samples was minimalized to 0.5 - 5.0 K. A problem with measuring on water saturated material is drying as this will dramatically lower the measured thermal conductivity. Examples of drying are shown for samples 123 and 200 in Paper 4, Figure 7. The effect of drying is also seen in Paper 5, Table 1 where thermal conductivities of synthetic quartz samples measured in both water saturated and dried condition are presented. The measured thermal conductivity of one of the samples (sample 20 -63 µm B) was reduced by 68 % from originally 1.42 W/m-K to 0.45 W/m-K after drying. For some of the repeated measurements a considerable reduction in the thermal conductivity was observed and related to drying. The values obtained after such reduction are not considered in this study.

During this study the reproducibility of the measurements has been tested. A distinction is made between *experimental error* and *sample error* (Davis, 1973). Experimental error reflects the uncertainty in the measurements by the divided bar apparatus itself. This error was found by repeated measurements on selected samples under identical conditions (Table 1).

Table 1. Experimental errors as obtained by repeated measurements on selected samples.

Presented in thesis	Sample*	Measured thermal conductivity W/m-K	Deviation %
Thesis study unpubl.	Quaternary clay, Gauldal, Trøndelag		
	Sample size: 25.0-25.0-6.0 cm ³	1.0022 / 1.0058	+ 0.4
	Sample size: 15.0-15.0-3.0 cm ³	1.3666 / 1.3883	+ 1.6
	Sample size: 5.0-5.0-3.0 cm ³	0.8673 / 0.8472	- 2.3
Paper 3	Clay-/ mudstones, England		
	Sample size: cube, l=3.0 cm		
	London clay, L1, (parallel, 27 °C)	1.1208 / 1.1483	+ 2.5
	Fullers Earth, Reigate, R2, (perpendicular, 27 °C)	0.7616 / 0.7552	- 0.8
Paper 4	Fullers Earth, Reigate R3, (parallel, 27 °C)	0.7660 / 0.7693	- 0.4
	Unconsolidated sediments, Vøring Basin		
	Sample size: cube, l=3.0 cm		
	Sample no. 186 (parallel, 46 °C)	0.882 / 0.862	- 2.3
Paper 5	Sample no. 200 (parallel, 41 °C)	0.728 / 0.728	0.0
	Hydrothermal quartz		
	Sample size: cube, l=3.0 cm		
	Massive B (perpendicular, 25°C/31°C)	3.764 / 3.676	- 2.3
	Massive B (parallel, 25°C/31°C)	3.957 / 4.000	+1.1

* measured direction to the layering and the mean temperature of the sample during the run is given in paranthesis.

Sample errors reflect uncertainties in the measurements due to the sampling and sample preparation process. This error was found by measuring parallel samples prepared from the most homogeneous material in this study (Table 2).

Table 2. Sample errors as obtained from measurements on parallel samples of the most homogeneous material in this study. The samples are cubes, $l=3.0$ cm.

Presented in thesis	Sample*	Measured thermal conductivity W/m-K	Deviation %
Paper 3	Clay-/ mudstones, England		
	Fullers Earth, Reigate, (perpendicular, 27 °C)	0.758 / 0.741 / 0.739	- 0.9 - + 1.6
	(parallel, 27 °C)	0.817 / 1.096 / 0.768	-14.1- +22.6
	Fullers Earth, Baulking (perpendicular, 27 °C)	0.711 / 0.682 / 0.660	- 3.6 - + 3.9
	(parallel, 27 °C)	0.806 / 0.819 / 0.769	- 3.6 - + 2.6
Paper 5	Hydrothermal quartz		
	Massive sample (perpendicular, 25 °C)	4.217 / 3.720	-11.8
	(parallel, 25 °C)	4.295 / 4.303	+0.2

* measured direction to the layering and the mean temperature of the sample during the run is given in paranthesis.

As seen in Tables 1 & 2 the experimental error was within 2.5 % for the tested samples while the sample error was within 3.9 % for four of the six parallel measurements. For the parallel measurements of Fullers Earth from Reigate and the perpendicular ones of the hydrothermal quartz, sample errors of +22.6 % and 11.8 % respectively were detected. These high errors might reflect inhomogenities in the material.

COMPARISON OF THERMAL CONDUCTIVITY MEASUREMENTS.

This study focus on the thermal conductivities of clays and clay- and siltstones. The measurements reported in Paper 2 and in a separate study of sandy sediments from the Ness Formation, Oseberg field (Midttømme et al., 1996), are plotted together with thermal conductivity data included in a commercial basin modelling program (confidential) and from McKenna et al. (1996) as a function of porosity (Figure 5). This figure shows that thermal conductivities measured in this study are considerably lower than the data for pure sandstones. The thermal conductivity measurements reported in Paper 2 are also slightly lower than data on shales from the Norwegian Shelf. It is noteworthy to point out that the Norwegian Shelf data were obtained by the needle probe technique. A discrepancy due to the method of measurement is discussed in Papers 1, 3 & 4. Methodological, mineralogical and textural factors which may explain the variation in thermal conductivities seen in Figure 5, are discussed in Papers 1, 2, 3, 4 & 5 in the thesis.

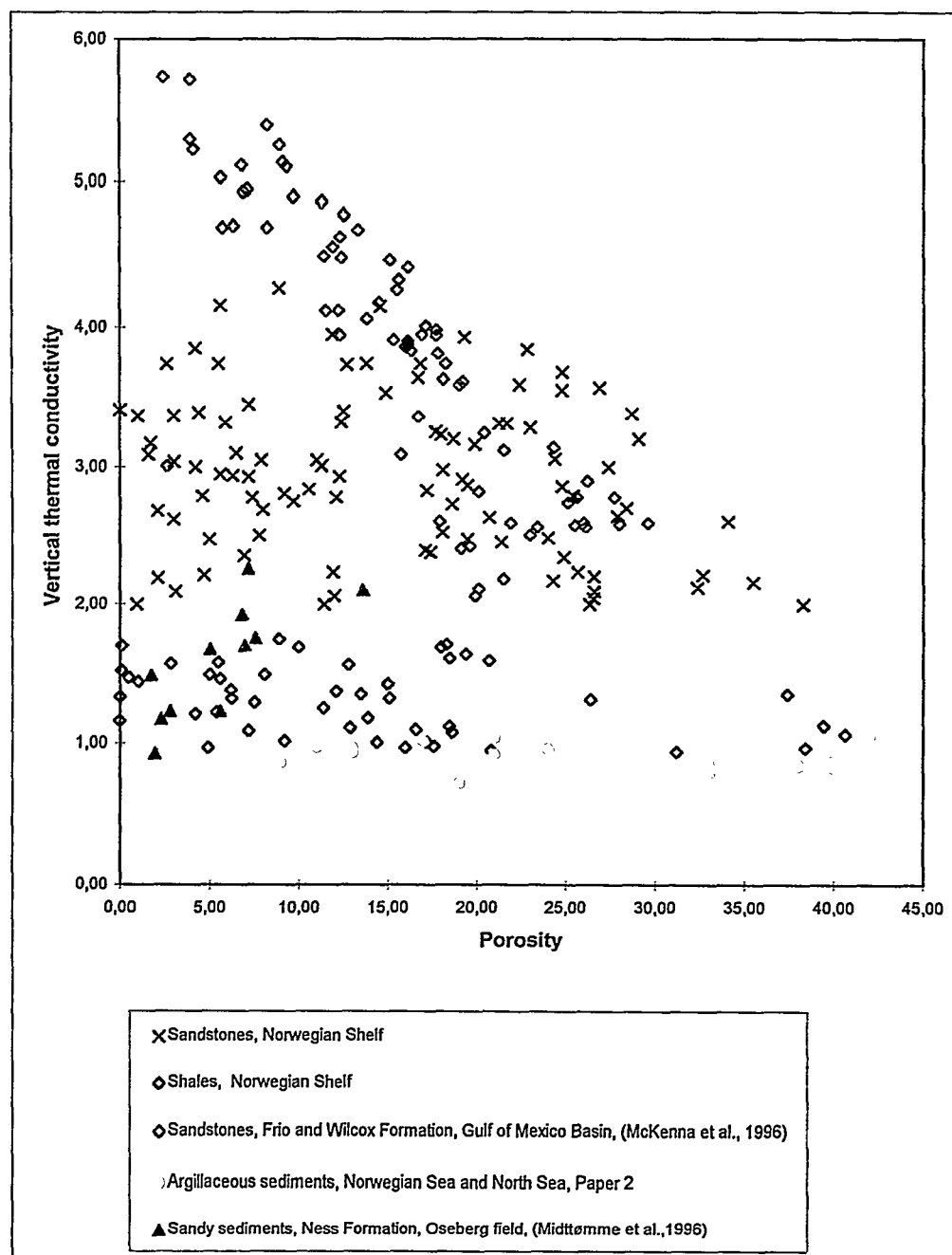


Figure 5. Comparison of measured thermal conductivities. Data from Norwegian Shelf is included in a commercial basin modelling program and is statistically treated by Seter (diploma thesis, NTNU, in prep.).

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Paper 1

Paper 1

Thermal conductivity of sedimentary rocks - uncertainties in measuring and modelling*.

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ABSTRACT

Thermal conductivity is a key parameter in basin modelling. There is still lack of knowledge about the thermal conductivity of sedimentary rocks, and in particular little available information exists on clay- and mudstones which normally make up 70-80% of the sedimentary basin. The uncertainties in the determination of thermal conductivities are partly due to problems in measuring and partly to difficulties in modelling thermal conductivity. To avoid unrealistic thermal conductivity measurements we suggest more comparative studies of the measurement methods, and a standardization of the preparation and experimental procedures. In the modelling of thermal conductivity our experience strongly indicates that the textural influence is underestimated by many of the existing models. Models based on the geometric mean model seem to be most successful so far, when the determination of matrix conductivity is restricted to the sediment type, mineralogy and texture of the sediments.

* In manuscript. Submitted to: *Mudrocks at the Basin Scale: Properties, Controls and Behaviour. Geological Society Special Publications.*

INTRODUCTION

Thermal conductivity, k , is a key parameter in temperature modelling, because it controls the conductive heat flow, the main mechanism of heat transfer in sedimentary basins. The thermal gradient by conduction is described by Fourier's law as inversely proportional to the thermal conductivity for a given heat flow (Equation 1).

$$q = -k \frac{dT}{dz} \quad (\text{eq.1})$$

q - heat flow (W/m²),
 k - thermal conductivity (W/m·K),
 dT/dz - temperature gradient.

Blackwell & Steele (1989) concluded that we do not have enough information to estimate mean thermal conductivity effectively for a section of sedimentary rocks and, if the mean conductivity cannot be accurately predicted, even the most sophisticated and appropriate modelling techniques are not sufficient for accurate temperature predictions. Today, there is still a lack of basic knowledge about the thermal conductivity of sedimentary rocks and, in particular, reliable information concerning mudstones and shales (e.g. Gallagher et al., 1997). In basin modelling there is still uncertainty which parameters affect the thermal conductivity. Until the correct parameters are found, attempts to develop thermal conductivity models without clear limitations are difficult. Measurements of thermal conductivity form the basis for understanding and modelling of the thermal conductivity in sedimentary basins. Lack of standard procedures or methods of measurement and quality control of the measurements seems to have resulted in poor quality of some published thermal conductivity measurements. According to Brigaud & Vasseur (1989), published data on thermal conductivities of clays are generally unreliable because no distinctions are made on the mineralogy and saturation conditions of the experiments.

This paper is a summary of the results obtained from the project "Shale and Claystones, Physical and Mineralogical Parameters in Basin Modelling" financed by the Norwegian Research Council and Statoil. Based on our experience from 6 years of thermal conductivity studies and measurements, mainly on mudstones, we will discuss problems with measuring and modelling of thermal conductivities and suggest improvements.

Example from North Sea.

The high sensitivity of the estimated thermal conductivity on the modelled temperature history is illustrated in Figure 1. The temperature history of a cross section from Northern North Sea is

estimated using BMT - Basin Modelling Toolbox, a basin modelling system developed by Rogaland Research and described by Fjeldskaar et al. (1990).

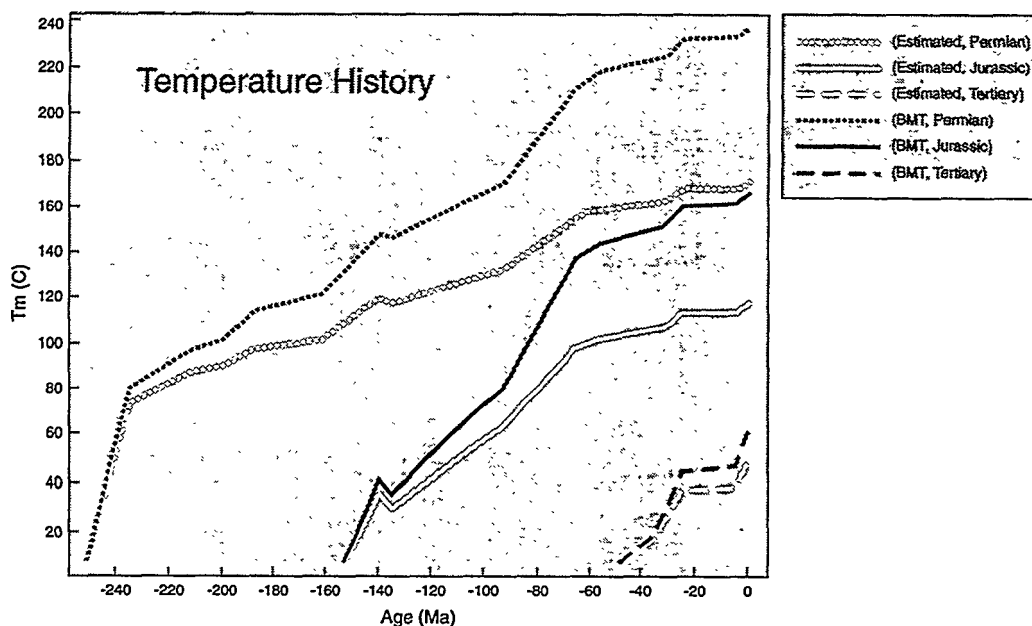


Figure 1. Temperature histories of three sediments (Permian, Jurassic Tertiary) in the North Sea Basin. Thermal conductivities are estimated by two methods: 1) Estimation by the geometric mean model from the mineral conductivities (Table 1), shown with white lines. 2) Estimations by the geometric mean model based on the BMT database of thermal conductivity measurements and mineralogy, shown with black lines.

Thermal conductivity is estimated by the geometric mean model (Equation 2).

$$k = k_f^\phi \cdot k_s^{(1-\phi)} \quad (\text{eq.2})$$

- k - thermal conductivity of the sediment (W/m·K),
- k_f - thermal conductivity of the pore fluid (W/m·K),
- k_s - thermal conductivity of the matrix (the solid part of the sediments) (W/m·K),
- ϕ - porosity (0.00 - 1.00).

The matrix conductivity (k_s) in this model is determined by two different methods: 1) By the geometric mean model from the mineralogy based on the mineral conductivities (Table 1) ("Estimated" in Figure 1), 2) Determined from a BMT database of thermal conductivity measurements based on the mineralogy ("BMT" in Figure 1).

Table 1. Thermal conductivity of common minerals and fluids in sedimentary rocks.

Mineral	Thermal conductivity W/m·K	Reference
Quartz	7.8	Horai, 1971
Calcite	3.4	Horai, 1971
Dolomite	5.1	Horai, 1971
Anhydrite	6.4	Horai, 1971
Pyrite	19.2	Horai, 1971
Siderite	3.0	Horai, 1971
K-feldspar	2.3	Horai, 1971
Albite	2.3	Horai, 1971
Mica	2.3	Horai, 1971
Halite	6.5	Horai, 1971
Kaolinite	2.8	Horai, 1971
Illite	1.8	Horai, 1971
Mixed layer I/S	1.9	Horai, 1971
Water (20 °C)	0.60	Schön, 1996
Oil	0.21	Jensen & Doré, 1993
Gas	0.079	Jensen & Doré, 1993
Air (20 °C)	0.026	Schön, 1996

The estimated temperature histories of three selected points on the cross section representing different geological ages are shown in Figure 1. The points represent the lower Tertiary (depth = 1650 m b.s.b.), upper Jurassic (depth = 5150 m b.s.b.) and the Permian (depth = 8600 m b.s.b.). The thermal conductivities are by both methods estimated by the geometric mean model with the same porosity data. By use of the thermal conductivity database to estimate matrix conductivity, the present day temperature for the Permian sediments is estimated to be about 70 K higher than the values obtained by using the geometric mean model to estimate matrix conductivity. A discrepancy of over 10 K is estimated for the present day temperature of Tertiary sediment.

MEASURING OF THERMAL CONDUCTIVITY.

Measured thermal conductivities of sedimentary rocks are presented in several handbooks and papers (e.g. Clark, 1966, Kappelmeyer & Hanel, 1974, Schön, 1996) (Table 2).

Table 2. Thermal conductivities of sedimentary rocks

(Clark, 1966).

Rock type	Locality	Thermal conductivity W/m·K			References
		n	range	mean	
Sandstone	Karoo Sandstone	7	1.46...3.22	1.97	Mossop & Gafner, 1961
	Jacobsville Sandstone	8	2.13...4.27	2.83	Birch, 1954
	Carboniferous Sandstone	6	2.51...3.22	2.77	Bullard & Niblett, 1951
Shale	Karoo Shale	6	1.97...2.87	2.38	Mossop & Gafner, 1961
	Berry No.1 Well, Kern Co Calif. 1000-5290 feet	14	1.17...1.76	1.49	Benfield, 1947
	Berry No.1 Well, Kern Co Calif. 5290-8780 feet	17	1.34...2.34	1.76	Benfield, 1947
	Carboniferous Shale	11	1.26...1.80	1.36	Bullard & Niblett, 1951

(Schön, 1996).

Rock type	Thermal conductivity W/m·K			References
	n	range	mean	
Sandstone	1262	0.90...6.50	2.47	Cermak & Rybach, 1982
	11	1.88...4.98	3.72	Jessop, 1990
	447	0.38...5.17	1.66	Dortman, 1976; Kobranova, 1989
Siltstone	3	2.47...2.84	2.68	Jessop, 1990
Clay-Siltstone	19	1.70...3.40	2.46	Cermak & Rybach, 1982
Claystone	242	0.60...4.00	2.04	Cermak & Rybach, 1982
Shale	377	0.55...4.25	2.07	Cermak & Rybach, 1982

Whereas Clark (1966) tabulated the thermal conductivities of sandstones in the range of 1.46-4.27 W/m·K based on 26 measurements, Schön (1996) included 1720 measurements of sandstones ranging from 0.38 W/m·K to 6.50 W/m·K. Except for a larger variation range, the increased number of thermal conductivity values has not improved our knowledge of the thermal conductivity of sedimentary rocks. Poor quality of the measurements is assumed to be one of the main reasons for the uncertainty related to the determination of the thermal conductivity, and is assumed to have caused many unreliable values, especially for shales and mudstones.

Methods of measurement.

There is no standard procedure or method to measure thermal conductivity of sedimentary rocks. Different methods of measurement are developed, where the two main techniques are the *divided bar method* and the *needle probe method*. The former method is a steady state method where the thermal conductivity is determined by Fourier's law (Equation 1) when there is a constant temperature gradient across the samples and the heat flow is stable. Different types of the divided bar apparatus have been developed. The method is considered as the most exact one (Johansen,

1975; Farouki, 1981; Brigaud et al., 1990) and is recommended by the International Heat Flow Commission wherever possible for competent cores (Beck, 1988). The needle probe method is a transient method. It was developed by Von Herzen & Maxwell (1959). A probe, which contains a heating wire and a thermistor, is inserted into the samples. The temperature of the sample is recorded as a function of time. From this temperature-time, curve the thermal conductivity of the material can be determined (Jessop, 1990). This method is easier and more rapid than the divided bar method, and less demands are made on sample preparation. The needle probe equipment is more standardized than the divided bar method.

Good contact between the samples and the laboratory equipment is important to prevent contact resistance which will be a source of error. Attaining satisfactory contact depends on the type and shape of the sample and the design of the apparatus and equipment. A smooth and well prepared sample surface is important, particularly for many of the divided bar apparatuses. Different types of waxes and fluids are used to improve the sample contact during measurements. The different designs of the equipment and apparatus make them suitable for different types of samples. A divided bar apparatus tested and calibrated for consolidated samples might therefore be carefully used for soft unconsolidated samples.

Sampling, preparation and measurements.

Even more important than the method is how the samples are prepared. An extreme case is the preparation method developed by Sass et al. (1971), where the samples are crushed to powder. The measurements are carried out on a suspension of powdered samples and water. This method has been used for the divided bar method (Sass et al., 1971), the needle probe method (Horai, 1971) and other transient methods (Middleton, 1994). An advantage with measuring on powdered samples is that it simplifies the sampling and the preparation process. Measurements can be carried out on rock fragments and cuttings. The main drawback by this method is that it does not account for the effect of texture.

Thermal conductivity of sedimentary rocks is in general measured on water saturated samples. The very low thermal conductivity of air (Table 1) makes the thermal conductivity of sedimentary rocks very sensitive to drying of the samples during the sampling, preparation and measurement process. The sampling and preparation process seems to be difficult and also critical for the measurement particularly for mudstone and shale samples. This has resulted in less (Table 2) and probably poorer thermal conductivity measurements of these fine grained sediments (Brigaud & Vasseur, 1989).

All methods of thermal conductivity measurement require heat transfer through the sample during measurement. This easily leads to an unstable condition since heat flow induces mass flow which makes a convective contribution to the heat flow and to some degree will cause drying of the sample. By keeping the temperature gradient across the samples low during measurement the measurement error due to mass flow is reduced. The risk of drying will also be dependent of the mean temperature of the samples during measurement. Measurements at high temperature will be more sensitive to drying.

The nature of the sample.

The anisotropic nature of sedimentary rocks is a point of uncertainty in the determination of thermal conductivity. Thermal conductivities parallel to the layering are more than double those measured perpendicular to the layering (Midttømme et al., 1996; Schön, 1996). The influence of the direction of heat flow on the measurements highlights the method of measurement and the method of sample preparation, particularly for anisotropic rocks, such as shale.

The inhomogenous nature of sedimentary rocks may cause problems in the determination of the thermal conductivity, mainly the uncertainty of upscaling of the sample. The question that arises is how representative a sample of 1-10 cm³ is for the sequence of rocks from which it was extracted (Gallagher et al., 1997).

Comparison measurements.

Comparative measurements between the needle probe and the divided bar methods have previously been reported. Agreement was obtained by Von Herzen & Maxwell (1959), Sass et al. (1971) and Brigaud & Vasseur (1989), while higher values of thermal conductivity were measured with the needle probe by Penner (1963), Slusarchuk & Foulger (1973), Johansen (in Farouki, 1981), Somerton, (1992) and Midttømme et al. (1997c). The discrepancy in these studies is in the range of 10-20 %. A constant deviation between the two methods was measured for unconsolidated sediments (Midttømme et al., 1997c) (Figure 2). This deviation was assumed to be due to a calibration error between the two methods of measurement, since other measurement errors such as drying or disturbances of the samples were assumed to cause a more random deviation.

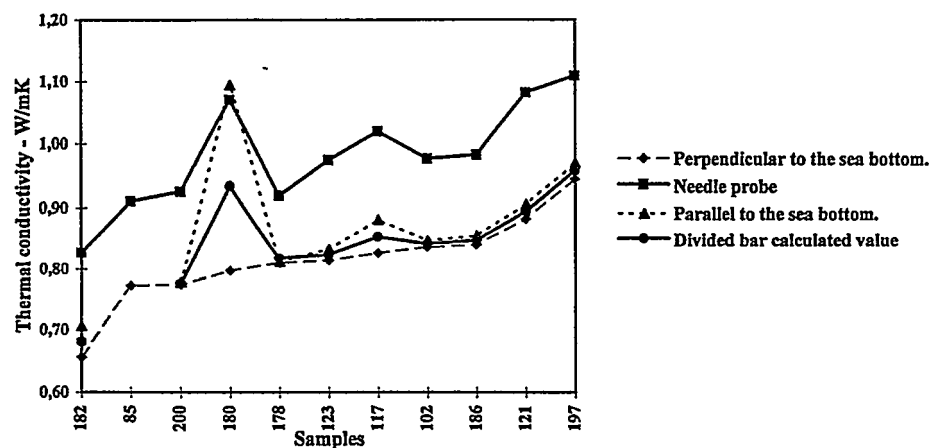


Figure 2. Comparative measurements with divided bar apparatus and needle probe on unconsolidated sediments (Midttømme et al., 1997c). The divided bar measurements are carried out parallel and perpendicular to the sea bottom. To compare those measurements with the needle probe measurements a mean value, k_m is calculated based on the equation for an ellipse ($k_m = \sqrt{k_{\perp} \cdot k_{\parallel}}$).

In a study of clays and mudstones from England comparative measurements were carried out by applying the divided bar apparatus, the needle probe and a transient method developed by Middleton et al. (1994) (Table 3).

Table 3. Comparative measurements on clay and mudstones from England (Midttømme et al., 1997b).

Sample	Thermal conductivity (W/m·K)			
	Divided bar apparatus NTNU	Needle probe ¹ University of Aarhus	Middleton's method	Bloomer's measurement (1981)
London Clay, perpendicular	0,83	0,84 (1)		2.45 ± 0.07
parallel	1.19	0.94 (3)		NP ² (5) ³
Fullers Earth, perpendicular	0,68	0,73 (3)		1.95 ± 0.05
parallel	0,80	0.98 (1)		NP/PB (41)
Kimmeridge Clay, perpendicular	0,97	1,21 (1)	0,89/0,96	1.51 ± 0.09
parallel	1.20	1.21 (1)	1,18/1,07	NP/PB (58)
Oxford Clay, perpendicular	0,79	1,19 (2)	0,84	1.57 ± 0.03
parallel	1.11	1.29 (3)	1.11	PB(11)

¹ The number in parenthesis gives the quality of the measurements, 1 is good and 3 is poor.

² Method of measurements, NP: Needle probe, PB: Divided bar

³ Number of measurements.

Previous measurements on these clays were published by Bloomer (1981). Two main discrepancies were found: Bloomer's measurements are considerably higher than the recently published measurements in Midttømme et al. (1997b). A discrepancy of over 100 % for Fullers Earth is most disquieting since this clay appears to be nearly homogeneous and isotropic. This discrepancy can therefore hardly be due to mineralogical nor textural variations of the measured samples.

Of the three recent measurements, the needle probe measurements differ from the two other ones. No systematic discrepancy is found between the needle probe and the divided bar apparatus measurements, but for the three anisotropic mudstones (London Clay, Kimmeridge Clay and Oxford Clay) a considerably lower thermal conductivity anisotropy ($a=k_H/k_L$) is obtained by the needle probe than by the two other methods. This discrepancy in the measured anisotropy is assumed to be due to the way heat is transferred through the samples by the different methods. In the needle probe method heat is transferred from a line source, while by the divided bar apparatus and Middleton's method it is transferred from a plate.

In the light of present day knowledge, more important than new thermal conductivity measurements are tests and comparative studies of the methods and procedures of measurements on all types of sedimentary rocks, and in particular on clays, mudstones and shales since those measurements are associated with the greatest uncertainties. More standardized procedures and documentation of sampling, preparation and measurement are important to ensure that the measured thermal conductivity is not affected by factors related to the measurement method.

MODELLING OF THERMAL CONDUCTIVITY.

In basin modelling the thermal conductivity in general has to be estimated. The accuracy of the modelled results depends on the rock information available, the accuracy of this information and the knowledge of how the rock parameters affect the thermal conductivity. Thermal conductivity of water saturated sediments depends mainly on porosity, mineralogy and texture, and to some extent on temperature and pressure (e.g. Blackwell & Steele, 1989; Midttømme et al., 1997a).

Porosity

A clear correlation, with increasing thermal conductivity with decreasing porosity, is observed between the porosity and thermal conductivity of sedimentary rocks (e.g. Brigaud & Vasseur, 1989). In a study of unconsolidated sediments, thermal conductivity could be estimated within 80%

accuracy from the water content (Midttømme et al., 1997c). Rarely, studies with no clear correlation between the two parameters have also been published (Blackwell & Steele, 1989; Midttømme et al., 1997a).

Although the porosity is a well-known parameter, it is not so easy to determine accurately. Porosity can be determined from laboratory measurements, well-log data or compaction models. There seems to be some confusion regarding the different types of porosities; e.g. effective porosity, total porosity and water content (Griffiths et al. 1992; Midttømme et al. 1997b). This confusion will for some sediment types be a source of error in the determination of thermal conductivity.

The large variation of the fluid conductivities (Table 1) makes the pore fluid an important factor controlling the thermal conductivity (e.g. Somerton, 1992; Jensen & Doré 1993). We have in this study only considered water saturated samples. The influence of other pore fluid is therefore ignored.

Mineralogy.

Since minerals have different thermal conductivities (Table 1), the composition of the matrix will effect the thermal conductivity. The quartz content is considered as most important since quartz has a relatively high conductivity (e.g. Johansen, 1975; Somerton, 1992; McKenna et al., 1996). Thermal conductivity measured on fine grained sediments like clay, claystone and shale is, in general, lower than for coarser material and these low values have been related to a higher content of clay minerals in these samples (Gilliam & Morgan, 1987; Demongodin et al., 1991; Midttømme et al., 1997a). The content of clay minerals is also considered as a point of uncertainty since the behaviour of these minerals due to the transfer of heat is more complicated than for the other minerals (Midttømme & Roaldset, 1997a).

Texture.

The textural effect on thermal conductivity is more complex and more complicated to model than the effect of mineralogy and porosity. The effect of texture is in many studies considered as less important than the porosity and mineralogy (e.g. Brigaud & Vasseur, 1989; Somerton, 1992, McKenna et al., 1996; Gallagher et al., 1997).

Anisotropy.

Evidence of a textural effect is the measured anisotropy. Thermal conductivities measured parallel to the layering are more than double those measured perpendicular to the layering (Midttømme et al., 1996; Schön, 1996). Schön (1996) assumed three causes for this anisotropy:

1. crystal anisotropy of the individual rock forming minerals.

2. intrinsic or structural anisotropy resulting from the mineral shapes and their arrangement within the rock.

3. orientation and geometry of cracks, fractures and other defects.

The anisotropy of thermal conductivity ($a=k_p/k_L$) will on this assumption be a function of burial history, depositional environment and the mineralogy, mainly the content of clay minerals as these have the highest anisotropy (Table 4).

Grain size.

A correlation is observed between the grain size and the thermal conductivity (Rzhevsky & Norvik, 1971; Midttømme & Roaldset, 1997b; Midttømme et al., 1997b), with increasing thermal conductivity with increasing grain sizes of the samples (Figure 3) and increasing sand content of the clay samples (Figure 4). The grain size effect on thermal conductivity is logarithmic, with the highest effect for the finest grained samples (Rzhevsky & Norvik, 1971; Midttømme & Roaldset 1997b). For unconsolidated samples the grain size fractions, in particular the sand fraction, were found to have a strong effect on thermal conductivity, even greater than the complete mineralogy (Midttømme et al., 1997c).

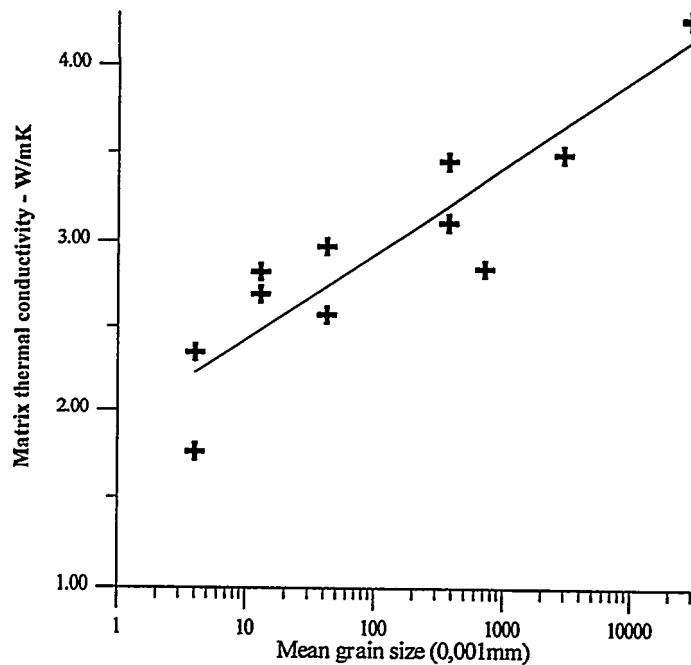


Figure 3. Estimated matrix conductivity, by the geometric mean model, plotted against the mean grain size of artificial quartz samples. The solid line shows the logarithmic regression, $R^2=0.86$ (Midttømme & Roaldset, 1997b).

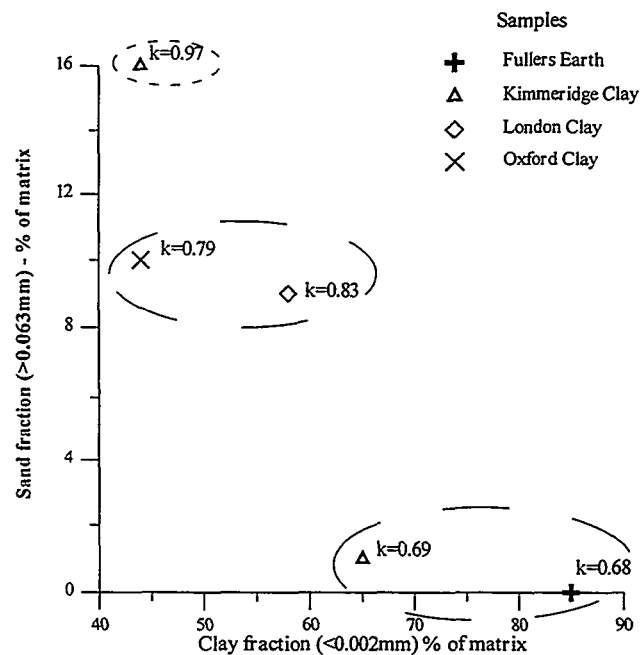


Figure 4. The clay fraction ($<2\mu\text{m}$) plotted versus the sand fraction ($>63\mu\text{m}$) for clay- and mudstones samples from England. The measured perpendicular thermal conductivities are shown (Midttømme et al., 1997b).

Table 4. Published anisotropy of thermal conductivity of some minerals.

Mineral	Symmetry	k_{\perp}	k_{\parallel}	anisotropy $a = k_{\parallel} / k_{\perp}$	References
		W/m·K	W/m·K		
Muscovite	monocline	0.84	5.1	6.1	Cermak & Rybach, 1982
Phlogopite (Mica)		1.7	4.9	2.9	Goldsmid & Bowley, 1960
Orthoclase	monocline	2.9	4.6	1.6	Cermak & Rybach, 1982
Gypsum	monocline	2.6	3.7	1.4	Cermak & Rybach, 1982
Calcite, 0°C	trigonal	3.5	4.0	1.1	Birch & Clark, 1940
50°C		3.0	3.4	1.1	Birch & Clark, 1940
		3.2	3.7	1.2	Cermak & Rybach, 1982
Dolomite	trigonal	4.7	4.3	0.9	Cermak & Rybach, 1982
Quartz, 0°C	trigonal	6.8	11.4	1.7	Birch & Clark, 1940
50°C		5.6	9.4	1.7	Birch & Clark, 1940
		6.5	11.3	1.7	Cermak & Rybach, 1982
Anhydrite	orthorhombic	5.6	5.9	1.1	Cermak & Rybach, 1982

Other textural factors.

Other textural factors like grain shape, grain arrangements, pore shape and pore sizes will to some extent affect the thermal conductivity (Andrews-Speed, et al., 1984; Brigaud & Vasseur, 1989). Since the grain size is found to influence the thermal conductivity, the pore size is assumed to have a corresponding effect on thermal conductivity. In fact the measured effect of grain size shown in

Figure 3 might be both a grain and pore size effect since the pore size will decrease with decreasing grain sizes of these artificial quartz samples. How the specific pore size factor will affect the thermal conductivity, whether an increase in the mean pore size will decrease or increase the rock thermal conductivity is not known.

There is a lack of studies which correlate thermal conductivity to the textural factors of sedimentary rocks. One of the few papers is that by Penner (1963), who measured higher thermal conductivity for flocculated marine clays than for dispersed lacustrine clays. He assumed that the variation was due to structural differences caused by the depositional environments.

The main problem due to the textural factors, as well as the mineralogical and physical factors, is to distinguish the different effects on thermal conductivity from each other. Another problem is to include the textural information in a model of thermal conductivity since most of these properties are difficult to quantify. Though these difficulties, more knowledge on the effect of the texture is important to improve the existing models of thermal conductivity. To make restrictions in the applications of the models due to the texture of the rocks might be a way to include these factors and to prevent unrealistic modelling results.

Temperature and pressure.

The effects of temperature and pressure on thermal conductivity are ambiguous. Temperature is found to affect thermal conductivity, but it is still uncertain how and to what degree. Both increases (Anand et al., 1973; Morin & Silva 1984; Gilliam & Morgan, 1987; Somerton 1992; Midttømme et al., 1997) and decreases (Balling et al., 1981; Brigaud et al. 1990; Demongodin et al. 1991) in thermal conductivities of clays and shales have been observed. Thermal conductivity of water increases with increasing temperature, while thermal conductivities of most of minerals decrease with increasing temperature (Clark, 1966; Balling et al., 1981; Demongodin et al., 1993). Therefore the thermal conductivity of water saturated rocks is assumed to vary widely depending upon the proportion of water to the solid part of the matrix.

An increase in measured thermal conductivity with increasing pressure has been observed (e.g. Anand et al., 1973, Gilliam & Morgan, 1987). This increase is assumed to be due to better grain to grain contacts at higher pressures.

A reason for the uncertainties related to the temperature and pressure effects on thermal conductivity might be how the determination methods account for the volume changes of the samples. Changes in pressure and temperature will induce volume changes of the pore fluid and the matrix. How the methods restrict these volume changes is important for the measured result, since

heat is mainly transferred by grain to grain contacts. A major problem with measurements at high temperature or high pressure is drying of the samples.

Models.

Many models are developed to estimate thermal conductivities from other known parameters. However, no universal model for the thermal conductivity of sedimentary rock has yet been found. The models can be grouped in three types (Somerton, 1992).

1. Mixing law models.
2. Empirical models.
3. Theoretical models.

Mixing law models combine values of the thermal conductivity of the rock matrix (k_s) with the conductivity of the pore fluid (k_f) on the basis of porosity. These models are of a general character and might be used for all sediment types. Thermal conductivity is in empirical models related to measured physical parameters, log data and to laboratory data. These methods have their shortcomings in that the resulting models may be applicable only to a particular suite of rocks being investigated (Somerton, 1992). Theoretical models are based on heat transfer theory for simplified geometries. The difficulty with these models is the degree of simplification necessary to obtain a solution. There is still a lack of detailed knowledge on how the heat is transferred through sedimentary rocks, in particular what happens in the transitional phase between grain-pore and grain-grain. Preferably, one would use a theoretical model to describe the physics of heat conduction, but sufficiently reliable models have not yet been developed, and empirical modifications of the equations are needed (Zimmerman, 1989; Somerton, 1992).

The mixing law models have dominated in the recent thermal conductivity studies. The three basic mixing law models are the arithmetic mean (Equation 3), geometric mean (Equation 2) and the harmonic mean (Equation 4).

$$k = \phi k_f + (1 - \phi) k_s \quad \text{eq. 3}$$

$$\frac{1}{k} = \frac{\phi}{k_f} + \frac{(1 - \phi)}{k_s} \quad \text{eq. 4}$$

The harmonic and arithmetic mean models are based on parallel and series arrangement of the components relative to the direction of heat flow (Figure 5). These two models are used, among others, by Vacquier et al. (1988), Somerton (1992), Pribnow & Umsonst (1993) and McKenna et al. (1996). The values estimated by these models are assumed to give the upper (k_{max}) and lower

(k_{min}) bound of thermal conductivity for a rock of given composition (Woodside & Messmer, 1961; Zimmerman, 1989 Schön, 1996). The geometric mean model gives a mean value of the arithmetic

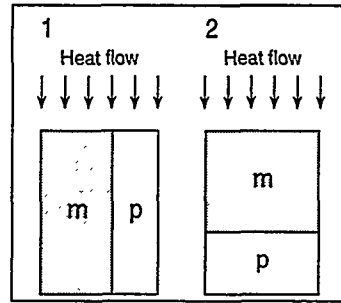


Figure 5. Sheet models of the two mixing law models. 1) arithmetic mean model, $k_{arith}=k_{II}$
2) harmonic mean model, $k_{harm}=k_{II}$, m- matrix, p- pore fluid (Schön, 1996).

and harmonic means. This model is the most widely used model by among others, Woodside & Messmer (1961), Sass et al. (1971), Balling et al. (1981), Brigaud et al. (1990), Demongodin et al. (1991), McKenna et al. (1996) and Midttømme et al. (1997c).

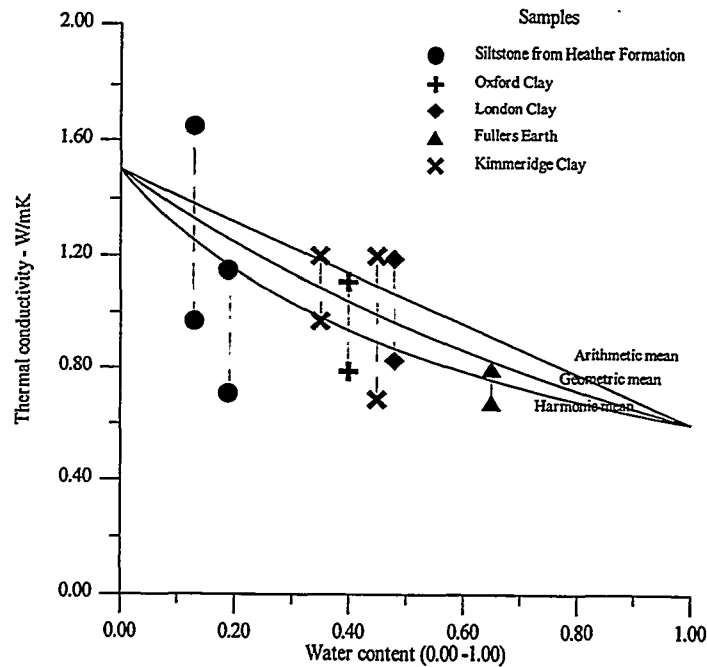


Figure 6. Thermal conductivity estimated by the arithmetic, geometric and harmonic mean model plotted versus water content. $k_f=0.60$ W/m·K, $k_s=1.50$ W/m·K. Parallel and perpendicular measured thermal conductivities of 5 samples are shown.

The main criticism of the geometric mean model is that it does not take account for the texture of the samples, and therefore is valid only for isotropic rocks (Brigaud & Vasseur, 1989; Somerton, 1992). The harmonic, arithmetic and geometric mean models are plotted as a function of the water content, together with 5 measurements of parallel and perpendicular thermal conductivities (Figure 6). Even for these claystones and siltstones the measured anisotropies are, except for Fullers Earth, higher than the theoretically maximum values based on arithmetic and harmonic means ($a_{max} = k_{aritm}/k_{harm}$). An explanation for this underestimate is that the arithmetic and harmonic mean models only take account of the structural arrangement of the pores and the matrix within the rocks and not to the crystal anisotropy of the individual rock forming minerals (Table 4), which are most important for the anisotropy effect of clay and mudstones (Demongodin et al., 1993). To take account of this crystal anisotropy effect, a higher parallel matrix conductivity ($k_{s||}$) than perpendicular matrix conductivity ($k_{s\perp}$) has to be used. By using the arithmetic and harmonic mean models, the estimated anisotropy depends on the value of matrix conductivity (k_s) (Figure 7). A low matrix conductivity gives low values of thermal conductivity. The opposite is often measured, where shales and claystones with low matrix conductivity have highest anisotropies. The most important anisotropic effect of thermal conductivity is not taken account of by using the arithmetic and harmonic mean models. From this assumption of the anisotropy, we prefer the geometric mean model, used with a higher matrix conductivity parallel than perpendicular to the layering to account for the thermal conductivity anisotropy.

The uncertainty related to the choice among the three mixing law models depends on the ratio k_g/k_f and porosity. For water saturated samples, where the fluid conductivity is assumed constant, the k_g/k_f ratio is determined by the matrix conductivity. According to Woodside & Messmer (1961), Lovell (1985) and Ungere et al. (1990), the geometric mean is valid only if the k_g/k_f ratio is not too large. For ratios greater than 20 the geometric mean model tends to substantially overestimate the measured values. The model was for this reason proven correct for clays with low matrix conductivity (Morin & Silvia, 1984). Thermal conductivities are plotted with the arithmetic, geometric and harmonic mean models as a function of the porosity in Figure 7. Thermal conductivity of the fluid is set equal to water conductivity ($k_f=0.60$ W/m·K) and the matrix conductivity (k_s) is constant equal a) 1.0 W/m·K, b) 2.5 W/m·K or c) 5.0 W/m·K. The deviation between the geometric mean model and the two other mixing law models is shown for porosities of 10%, 20%, 40% and 60% respectively. This discrepancy in estimated thermal conductivity varies from 1% to 68%. The highest sensitivity of the choice of mixing law models is for the highest matrix conductivity in the porosity range of 40-60 %.

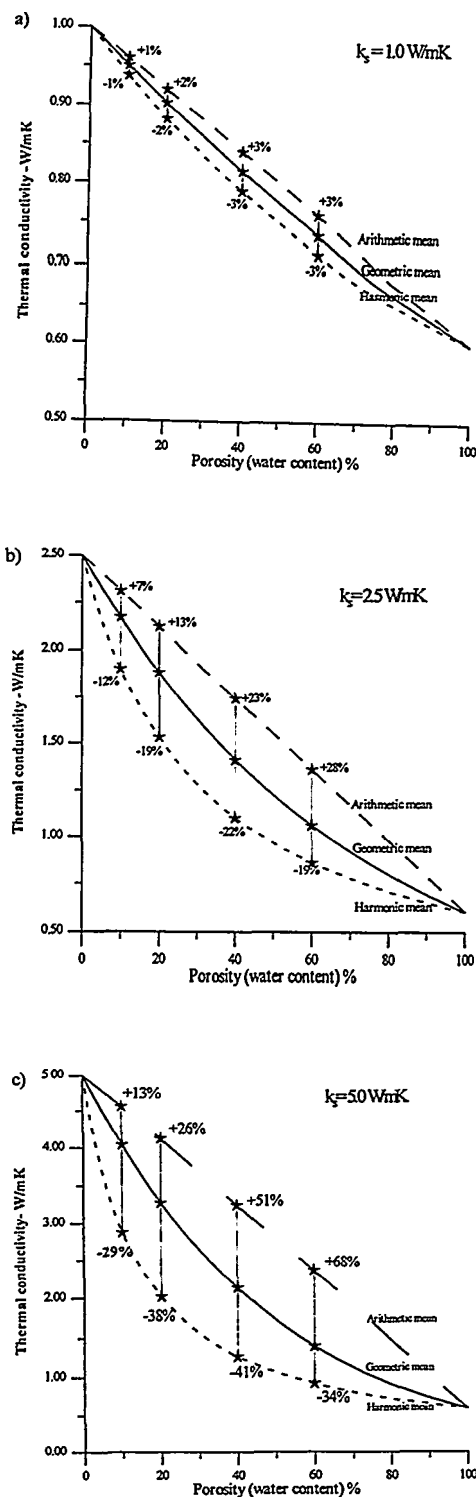


Figure 7. Thermal conductivity estimated by the arithmetic, geometric and harmonic mean model plotted versus porosity where $k_f = 0.60 \text{ W/m-K}$, and $k_s =$ a) 1.0 W/m-K , b) 2.5 W/m-K , and c) 5.0 W/m-K . The discrepancies between the geometric mean model and the two other mixing law models for porosities of 10 %, 20%, 40% and 60% are shown.

The matrix conductivity (k_s) is a point of uncertainty in mixing law models. This parameter has to take account of the mineralogical and textural effects on the thermal conductivity. Different values and models of matrix conductivity (k_s) have been used. In the simplest geometric mean models matrix conductivity is set as constant (Table 5), while matrix conductivity in complex models is estimated from the mineralogy (e.g. Brigaud & Vasseur, 1989; McKenna et al., 1996) and by use of mineralogy and grain size fraction (Midttømme et al., 1997c) (Table 6).

Table 5. Thermal conductivities used in the geometric mean equation.

Sample	Matrix conductivity (k_s) W/m·K	Water conductivity (k_p) W/m·K	References
Shale	2.35	0.60	Sekiguchi, 1984
	1.9		Grigo et al., 1993
Sandy shale	2.1		Grigo et al., 1993
Clay, claystone, shale	3.43	0.46	Balling et al., 1981
Clay	1.2-1.4	0.60	Demongodin et al., 1991
	1.1		Grigo et al., 1993
Claystone	1.5-3	0.56	Chapman et al., 1984
Siltstone	3.2		Grigo et al., 1993
Mudstone, siltstone	2.5	0.61	Bloomer, 1981
Sandy siltstone	2.49	0.60	Sekiguchi, 1984
Sandy mudstone	3.0	0.61	Bloomer, 1981
Shaly sandstone	2.66	0.60	Sekiguchi, 1984
Muddy sandstone	3.2	0.61	Bloomer, 1981
Sandstone	4.88	0.69	Balling et al., 1981
	6.60	0.60	Demongodin et al., 1991
	5-7	0.56	Chapman et al., 1984
	3.4		Grigo et al., 1993
Quartzose sandstone	7.96	0.60	Sekiguchi, 1984
Quartz sandstone	3.7	0.61	Bloomer, 1981
Carbonate	3.24	0.54	Balling et al., 1981
	3.0	0.59	Matsuda & Herzen, 1986
Limestone	3.2	0.61	Bloomer, 1981
	3.2	0.60	Demongodin et al., 1991
	3.6		Grigo et al., 1993
167 wells North Sea	0.8-8.3	0.60	Andrews-Speed et al., 1984
Gulf of Mexico	2.02	0.63	Sharp & Domenico, 1976
Sedimentary rock	2.51	0.58	Smith & Chapman, 1983
	1.7-4.2	0.4	Lerche, 1993

The accuracy of the estimate of the matrix conductivity depends on the rock information available. Of even greater importance is the right choice of model. Disagreements between estimated and measured thermal conductivities are shown for clay- and mudstones (Figure 8) and unconsolidated sediments (Figure 9). The thermal conductivities in these studies were estimated by the geometric mean model, where matrix conductivities were estimated from the mineralogy (Table 6). From the assumptions that the measurements in these studies are correct, the model fails to predict the thermal conductivity for these samples. Somerton (1992) assumed a basic difference in the thermal

Table 6 Advanced models of matrix conductivity from mineral and grain size conductivities.

	Samples	Horai (1971) Pulverized samples	Brigaud & Vasseur (1989) Sandstones and artificially recompacted clay samples	Midttømme et al., (1997a) Argillaceous sediments from North Sea	Midttømme et al., (1997c) Unconsolidated sediments from Vøring Basin $R^2=0.864$ $R^2=0.882$	
k_r			0.60	0.60	0.60	0.60
k_s	Quartz	7.8	7.70 ± 0.88	1.01	5.03	6.82
	Feldspar	2.3		1.02	2.97	3.49
	Calcite	3.4	3.26 ± 0.23		1.68	3.62
	Dolomite	5.1	5.33 ± 0.26		1.64	
	Pyrite	19.2		1.41		
	Kaolinite	2.8	2.64 ± 0.20	0.91	0.08	2.80
	Chlorite	5.1	3.26 ± 0.25			
	Smectite		1.88 ± 0.13	1.42	3.34	1.61
	Illite	1.8	1.85 ± 0.23	1.42	3.34	1.61
	>63 μ m					5.79
	2 μ m-63 μ m					1.52
	<2 μ m					1.89

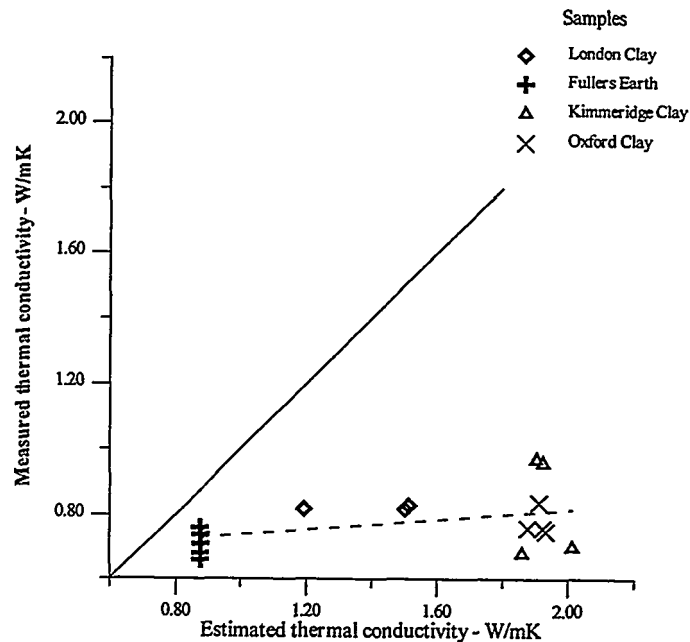


Figure 8. Estimated thermal conductivity versus measured thermal conductivity for clay and mudstones from England. The solid line is the unity line (1:1). The dotted line is the regression line (Midttømme et al., 1997b).

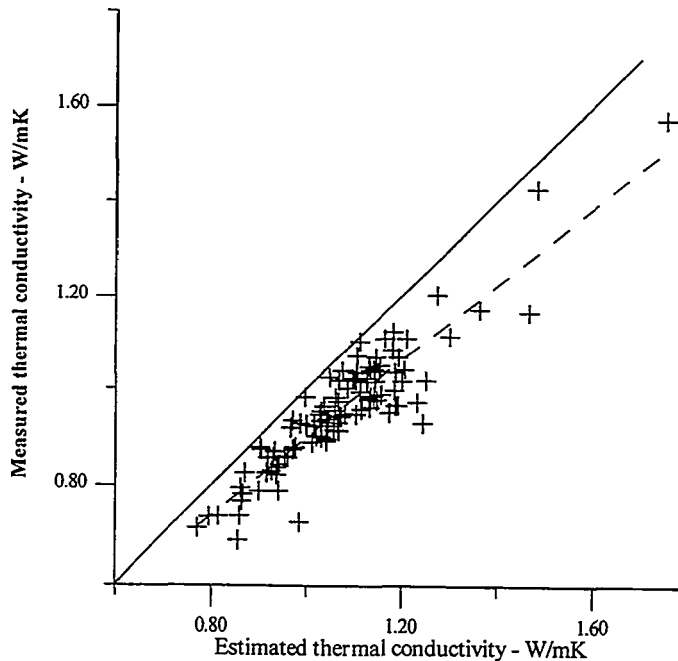


Figure 9. Estimated thermal conductivity versus measured thermal conductivity for unconsolidated sediments from Vøring Basin. The solid line is the unity line (1:1) The dotted line is the regression line (Midttømme et al., 1997c).

characteristic of consolidated rocks and unconsolidated sand. He therefore considered modelling the two systems separately. Midttømme et al. (1997a) assumed that quartz grains isolated in a clay matrix contribute less to the rock conductivity than quartz grains in contact with another. A distinction between matrix supported and grain supported sediments in modelling of the thermal conductivity was suggested by Eirik Vik (pers. comm., 1997). Because of differences in heat transferred through sedimentary rocks, no universal model of thermal conductivities exists today. All models are to some degree restricted either to specific rock types, in variation of ranges of the parameters or location. The restrictions in the mixing law models are caused by the estimation of matrix conductivity. According to Andrews-Speed et al. (1984), the matrix conductivity varies by one order of magnitude from 0.8 to 8.3 W/m·K (Table 5). To model these variations we suggest the development of specific matrix conductivity models for the different types of matrix. For some types of sediments a constant matrix conductivity might save the purpose. For other sediments types the mineralogy, depositional environment, grain size distribution etc., seems to affect the matrix conductivity and might be taken into account in the thermal conductivity model.

CONCLUSION.

Temperature cannot be predicted accurately in sedimentary basins, without knowledge of the thermal conductivities of the sedimentary sequences. There are still uncertainties related to the determination of thermal conductivities. Discrepancies in the thermal conductivity measurements are observed. This warrants more basic studies; i.e. validity of the method of measurements due to sediment type. A standardisation of the procedures of sample preparation and experimental conditions is needed to prevent unrealistic measurements.

No universal model of thermal conductivity exists today, and it will be difficult to develop such a model since the different sediment types seem to have basic differences in the heat transfer. Models based on the geometric mean model seem to be best so far. The effect of porosity on thermal conductivity can be taken into account by this model. The matrix conductivity (k_s) in the model depends on the mineralogy and texture of the sedimentary rocks. Our experience with clays and mudstones shows that the textural influence on thermal conductivity is underestimated by many of the existing models. How the different mineralogical and textural factors will affect thermal conductivity depends on the sediment types, lithology and texture. To define the range of application for the models due to type and texture of sediment is important to obtain realistic estimates applicable in basin modelling.

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Paper 2

Thermal conductivities of argillaceous sediments

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Abstract: Thermal conductivities of selected samples of shales, clay- and mudstones from the Norwegian Continental Shelf have been measured with a divided bar apparatus. The samples investigated are from conventional cores and side wall cores. Thermal conductivities for water-saturated samples measured perpendicular to the layering vary from 0.79 to 1.14 W/m K. The conductivities measured parallel to the layering are up to 1.7 times higher than those measured in the perpendicular direction. The investigation also confirms that the temperature has an influence on the conductivity. A model to predict thermal conductivity, based on water content and mineralogy has been proposed and tested.

Thermal conductivity of sediments is a key parameter in many studies of sedimentary basins because it controls the conductive heat flow, and therefore also the temperature distribution in sediment successions. Great efforts have been made to determine sediment conductivity both from laboratory measurements and from calculations from other known parameters. Still, there is lack of knowledge about the thermal conductivity of sedimentary rocks, and in particular little available information exists on the influence of clay minerals (Brigaud & Vasseur 1989).

The variation of the thermal conductivities of sediments is found to depend mainly on mineralogy, porosity and texture (Woodside & Messmer 1961; Anand *et al.* 1973; Johansen 1975; Farouki 1981; Brigaud & Vasseur 1989). Temperature will also have an influence on the conductivity (Anand *et al.* 1973; Gilliam & Morgan 1987; Blackwell & Steele 1989; Demongodin *et al.* 1993).

Factors influencing the thermal conductivity

Mineralogy

Mineralogy is the most important factor controlling thermal conductivities of sedimentary rocks. Thermal conductivities of selected rock forming minerals from Brigaud & Vasseur (1989) are shown in Table 1. These results are comparable with measurements by Horai (1971) and values applied in the basin modelling system (BMT) developed at Rogaland Research (Fjeldskaar *et al.* 1990).

Rocks with greater proportions of the clay minerals smectite, illite and mixed layer illite/smectite will have lower conductivities than rocks with the same proportion

of other minerals specially quartz and pyrite. The low conductivities of smectite and illite have been explained by the layering of the minerals (Blackwell & Steele 1989; Demongodin *et al.* 1993) although kaolinite and chlorite have the same layered structure but do not have such low thermal conductivities. The various clay minerals affect pore spaces in different ways, whether they are laminated, dispersed, in pore lining or in pore bridging. These structural differences may explain the differences in conductivity between the clay minerals.

Water content (porosity)

Thermal conductivity of water is 0.60 W/m K at 20°C and lower than the conductivity of the minerals. Thus, a decrease in water content would lead to an increase in the thermal conductivity of sediments. Because of the smaller

Table 1. Conductivity of rock forming minerals (Brigaud & Vasseur 1989)

Mineral	K (W/m K)
Quartz	7.7
Feldspar	2.3
Pyrite*	19.2
Calcite	3.3
Dolomite	5.3
Anhydrite	6.3
Chlorite	3.3
Kaolinite	2.6
Smectite	1.9
Illite	1.8
Illite/smectite	1.8

* Horai (1971)

difference between thermal conductivity of water and clay minerals, the effect of water content is less for low conductive materials such as shales and claystones, than for high conductive sediments as quartz rich sandstones.

Porosity is a more common used factor instead of water content when considering percentage of water in water saturated samples. Porosity is the volume of the pores in the material while water content includes all water in the material, also bound and constitutional water.

Texture

Sedimentary rocks are inhomogenous and anisotropic. The thermal conductivity will vary on micro scale within the single sediment layer, and also, with orientation to the layering. The difference in the conductivities measured parallel to and perpendicular to the layering, the anisotropy effect, is found to be considerable (Gilliam & Morgan 1987; Prestholm & Fjeldskaar 1993). Variation

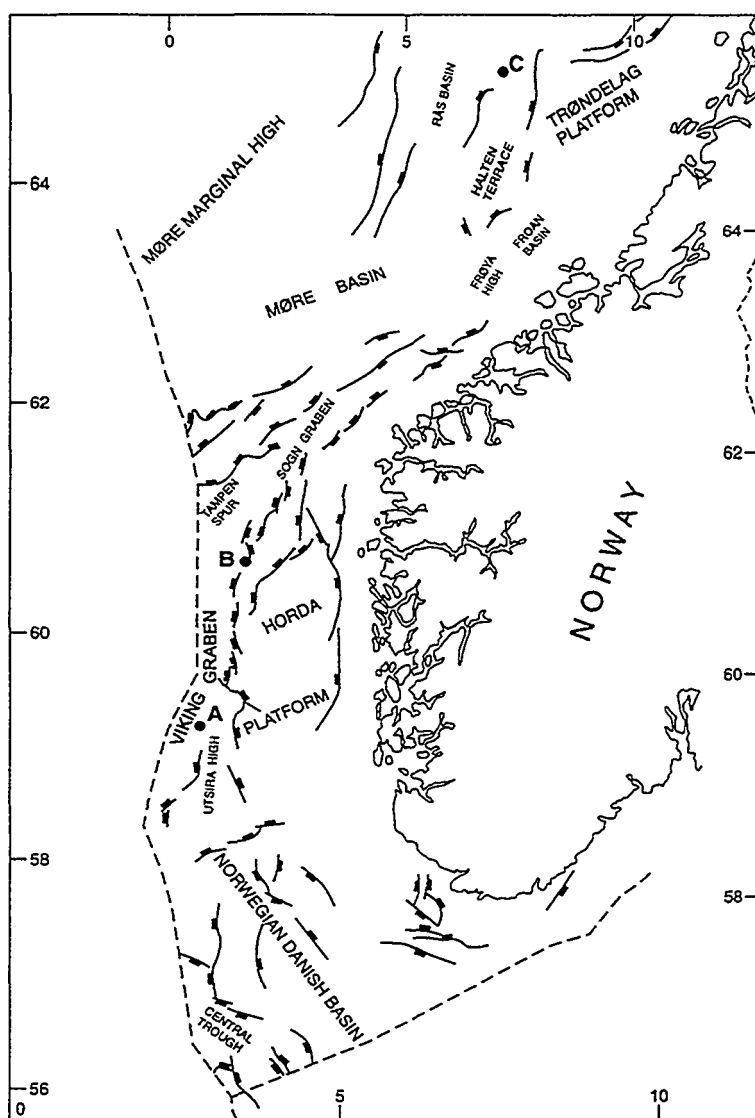


Fig. 1. Location of the three wells on the Norwegian Continental Shelf.

in conductivity caused by the texture can be divided into effects of crystal orientation for a given mineral and effects of small-scale heterogeneities within a given lithology (Demongodin *et al.* 1993).

Temperature

Variation in temperature will induce changes in bulk conductivity. (Anand *et al.* 1973; Balling *et al.* 1981; Demongodin *et al.* 1993). The actual temperatures in the economic zones of sedimentary basins range from 0°C to about 200°C. Somerton (1992) reported moderate negative gradients of thermal conductivity with temperature for high conductive rocks whereas small positive gradients for low conductivity rocks. Gilliam & Morgan (1987) measurements on shales show a slight increase in thermal conductivity with increasing temperature up to about 90°C. Both studies were based on experimental data from laboratory measurements. The effect of temperature of *in situ* conditions of the material may be more complex because the temperature also will influence other chemical and physical factors which may effect thermal conductivity. There is assumed to be two processes which will occur and effect thermal conductivity when increasing the temperature: the activity of molecules and atoms will increase and increase the thermal conductivity and to some extent there will be drying of the samples with increasing temperature which will decrease the conductivity.

Theoretical modelling of thermal conductivity

Various models have been proposed for estimating the thermal conductivity of sedimentary rocks. One of them, the geometrical mean model, has been shown to predict satisfactorily the conductivity, at least when anisotropy effects can be neglected (Woodside & Messmer 1961; Johansen 1975; Brigaud & Vasseur 1989; Demongodin *et al.* 1991). The geometric mean is a simple model which only takes account of the thermal conductivity of the matrix, k_s , thermal conductivity of the water, k_w , and water content, w . The bulk thermal conductivity of a water saturated rock is k given by Equation (1):

$$k = k_w^w \cdot k_s^{(1-w)} \quad (1)$$

where k_w is 0.6 W/m K.

Material investigated

20 mudstone samples from three wells (A, B and C) on the Norwegian Continental Shelf were investigated (Fig. 1).

Samples from well A are of Tertiary mudstones. The well is situated on the northwestern flank of the Utsira

High in the North Sea. The samples were prepared from side wall cores. The sampling interval is 1200–2500 m(RKB). Mineralogical, petrological and petrophysical investigations of the samples are reported by Tyridal (1994). The material consists of sandy mudstones where fragments of light claystones and grains of quartzite are randomly distributed in a darker clayey grey matrix. The fragmental character of the sediments is probably a result of mass flow caused by a turbidity current. Smectitic illite/smectite mixed layer minerals are found to be the dominating mineral. No laminations are visible. The side wall cores were contaminated with drilling fluids, and barite from the drilling fluids complicated the mineral identification by X-ray diffractograms.

Samples from well B are cut from conventional core samples from the Upper Jurassic Heather Formation. The well is located on the western flank of the Horda Platform. The sampling interval is 2125–2169 m(RKB) and the water depth is 147 m. The samples have been investigated by Zhang *et al.* (1992) and Roaldset & Gjelsvik (1993). The Heather Formation samples represent moderately to poorly sorted micaceous sandy siltstone. The material has a poorly developed lamination modified by bioturbation. The main constituents are quartz, feldspar and mica in a clayey matrix.

Well C is drilled on Haltenbanken off Mid-Norway. The two samples investigated from this well were cut from a conventional core from the Upper Cretaceous succession at a depth of 2437 m(RKB). The samples are fissile mudstones with a clay mineral content of 30% and a quartz content of 42%.

Laboratory measurements

Thermal conductivities were measured with a divided bar apparatus developed at Department of Refrigeration Engineering, Norwegian University of Science and Technology, and described by Brendeng & Frivik (1974) (Fig. 2). As the equipment originally was designed for larger samples a slightly modified method was applied where the samples were measured against a reference sample.

The samples were measured in water saturated state. To reduce the effect of water movement, the temperature gradient across the samples was minimalized to 1.0–3.5 K. The sizes of the samples were cores with radius 2.5 cm and length 3.0 cm for A and cubes with sides 3.0 cm for B and C samples.

To test the influence of the temperature on the conductivity the samples were measured at different mean temperatures. All samples were tested at two or three different mean temperatures between 10–60°C.

The mineralogy was determined by standard X-ray diffraction techniques described among others of Brindley & Brown (1980) and Moore & Reynolds (1989). The

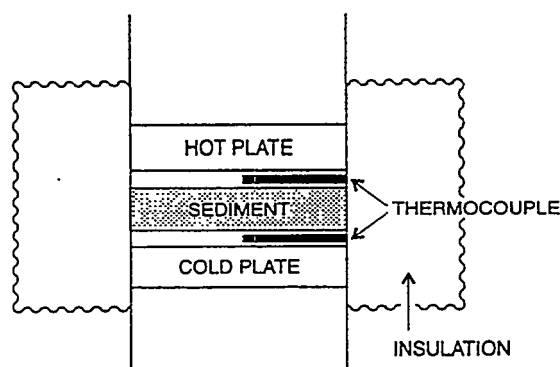


Fig. 2. A section through the divided bar apparatus.

diffraction patterns were interpreted manually by calculating the areas of the characteristic peaks of the untreated diffraction patterns. The peak areas were corrected by means of 'weighting factors' developed by H.G. Rueslåtten and generally applied at the X-ray Diffraction Laboratory at the Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology. The quantification is considered to be semi-quantitative with an average error in the order of 5–10% (Rundberg 1991).

Water content was calculated from measurements of bulk and grain densities (Equation 2).

$$w = 1 - \frac{\rho_m}{\rho_d} \quad (2)$$

where w is the water content (volume of water of total volume), ρ_m is the bulk density (g/cm^3) and ρ_d is the grain density (g/cm^3).

The densities were measured with pycnometer and calculated from the measured weight and volume of the samples. The samples were dried at 105°C before grain density was determined. Water content calculated in volume of water of total volume of material is often considered equal to porosity.

Results and discussion

The results of the measurements of water content, mineralogy and thermal conductivities are presented in Table 2.

The measured thermal conductivities vary in the range of 0.71–1.14 W/mK. The measured conductivities are similar to those reported by Gilliam & Morgan (1987) on shales from Green River Formation, USA, who also used a divided bar apparatus. However, the values of

Table 2. Results of thermal measurements together with water content, quartz and clay mineral contents

	Sample	Depth m RKB	Water content [%]	Content of clay minerals [%]	Quartz content [%]	Thermal conductivity perpendicular* k_{\perp} (W/mK)	Thermal conductivity parallel† k_{\parallel} (W/mK)	Anisotropy effect k_{\parallel}/k_{\perp}
Central North Sea	A1	1265	42	34	36	1.06		
	A2	1330	40	45	33	0.87		
	A3	1450	33	39	26	0.85		
	A4	1510	38	35	30	0.85		
	A5	1610	40	27	45	0.83		
	A6	1675	40	38	26	0.82		
	A7	1765	33	23	35	0.79		
	A8	1835	38	27	38	0.83		
	A9	1874	36	16	42	1.14		
	A10	2033	24	42	26	0.96		
	A11	2450	21	42	37	1.08		
	A12	2576	9	26	50	0.86		
Northern North Sea	B1	2125	13	50	21	0.97	1.65	1.70
	B2	2125	13	50	21	0.93		
	B3	2131	19	51	21	0.71	1.15	1.62
	B4	2155	11	58	18	0.97		
	B5	2161	15	70	13		1.20	
	B6	2169	17	54	19	1.02	1.54	1.51
Mid-Norwegian Shelf	C1	2437	21	30	42	0.92‡	1.08‡	1.17
	C2	2437	21	30	42	1.04‡	1.17‡	1.13

* Measured at temperature between 22 – 38°C .

† Measured 55° to the layering.

‡ Measured 35° to the layering.

this work are significantly lower than measurements on argillaceous sediments previously reported (Bloomer 1981; Brigaud & Vasseur 1989; Demongodin *et al.* 1993; Fjeldskaar *et al.* 1993). In their studies the conductivities were measured with the needle probe technique, which is considered as an easier, but not so exact, method for determination of thermal conductivities. The divided bar apparatus is considered more appropriate for measuring conductivity of anisotropic material than the needle probe technique.

The measured sample conductivity varied slightly with the test temperature. In tested temperature range of $+10$ – $+60^{\circ}\text{C}$ the conductivity varied from -0.016 to $+0.013\text{ W/m K}$ for increase of 10 K .

The low value of 0.71 W/m K of sample B3 differs from the other measured values. This value is probably due to drying of the material and is therefore omitted in the further discussion.

The effect of factors influencing the thermal conductivity

Water content

The measured thermal conductivities perpendicular to the layering are plotted against the water content in Fig. 3.

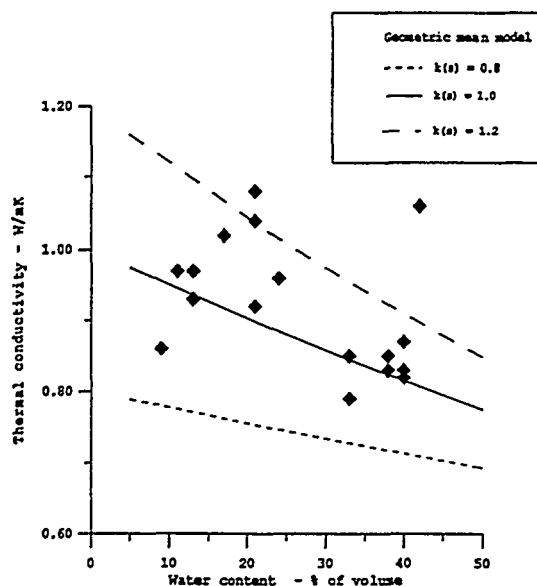


Fig. 3. Influence of water content on thermal conductivity. Geometric mean model (Eq. 1) calculated with thermal conductivity of water equal 0.6 W/m K and thermal conductivity of matrix, k_s , equal to 0.8 , 1.0 and 1.2 W/m K are also plotted.

The trend is a decrease in thermal conductivity with increasing water content. This agrees with the geometric mean model. The relationship between water content and thermal conductivity with depth for samples from well A as shown in Fig. 4 show a slight decrease in water content with depth. Thermal conductivity which was expected to increase with decreasing porosity, shows a more irregular pattern with depth and seems to be more strongly influenced by a change in the lithology.

Mineralogy

The influence of the quartz and clay minerals content of the thermal conductivities can be indicated from Figs 5 & 6.

No clear trend is found between the quartz content and measured thermal conductivity (Fig. 5). Taking into consideration the high conductivity of quartz (7.7 W/m K) and a quartz content up to 50% (sample A12), the measured thermal conductivities less than 1.0 W/m K are very low. An explanation for this may be that the fine quartz grains in these samples do not have the same increasing effect on thermal conductivity as reported for material with coarser quartz grains. As frequently observed by SEM investigations of argillaceous sediments the quartz may occur as isolated grains in a matrix of clay minerals. Seldom is grain to grain contact for quartz visible. Such contact is considered to be very important in transfer of heat by conduction.

According to the reported values of conductivity (Table 1), we have grouped the clay minerals in two groups, a low conductive group which includes illite,

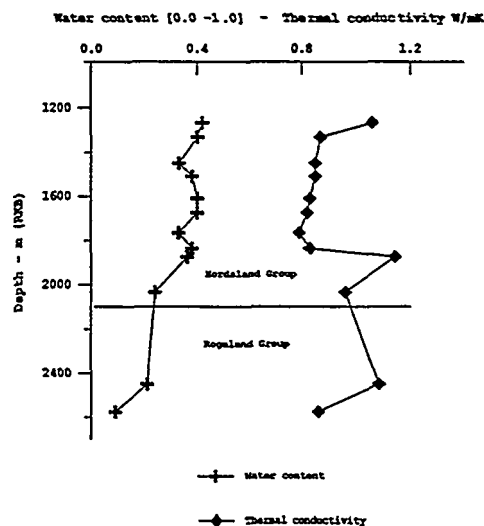


Fig. 4. Variation in water content and thermal conductivity with depth for the 12 samples from well A.

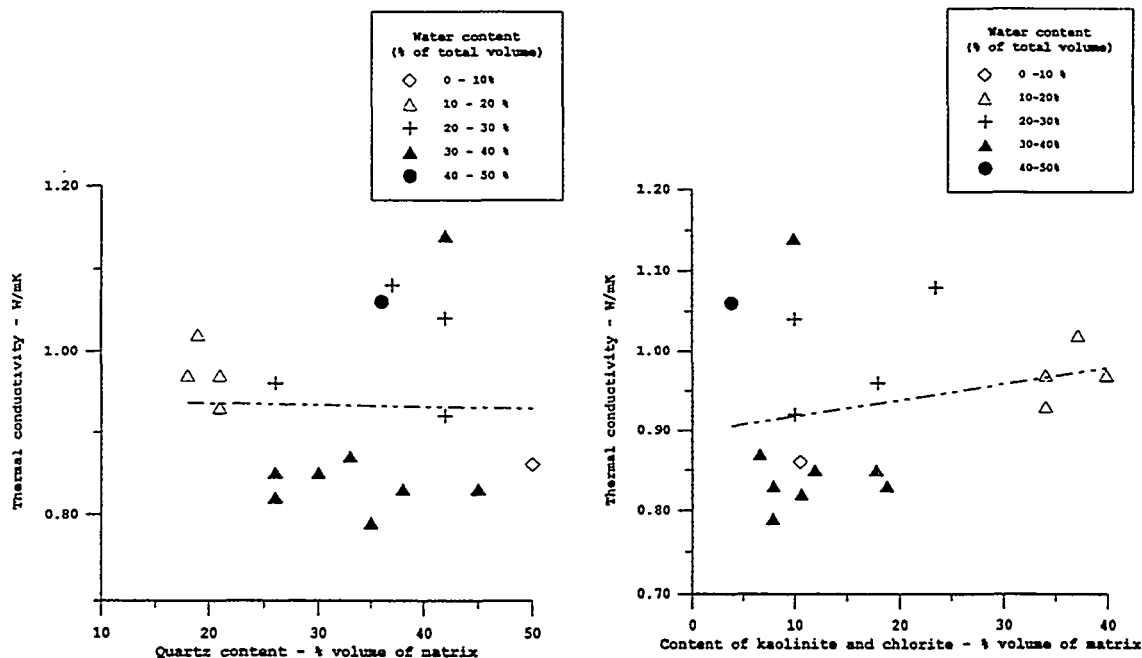


Fig. 5. Quartz content versus the measured thermal conductivities. Difference in water content is shown by different symbols. The linear regression line is marked with dotted line.

smectite and mixed layer illite/smectite (I/S) and an intermediate conductive group with kaolinite and chlorite. An increase in the volumetric proportion of the minerals in the low conductive group is assumed to reduce the bulk conductivity for clastic sedimentary rocks. Variation in the volumetric proportion of the intermediate group is expected to have low effect of the bulk conductivity.

The measured thermal conductivity show some irregularities when plotted against the two groups of clay minerals, but the general trend is a slight decrease with increasing volumetric proportion of the low conductive minerals. This trend is mainly due to the variations in the water content as shown with the different marks. For the samples with a water content in the range of 30–40% a slight increase in thermal conductivity with increasing contents of illite, smectite and mixed layer I/S is observed. We have no explanation for this trend. Figure 6 shows a slight increase with increasing volumetric proportion of the content of kaolinite and chlorite. This trend is also mainly influenced by the variations in water content.

Texture

Thermal conductivities measured parallel with the layering are considerably higher than the conductivities

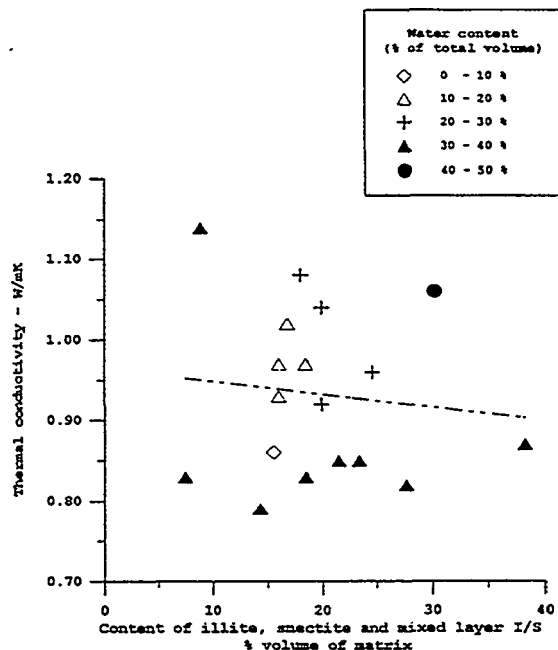


Fig. 6. Plots of clay minerals versus measured thermal conductivities. The linear regression line is marked with dotted line.

measured perpendicular to the layering. The anisotropy effect is found to be up to 1.70 (sample B1, Table 2). Because only few measurements are available, the anisotropy effect is not yet correlated to other factors, but the effect is assumed to be a function of the content of lamination and the microtextural arrangements of the clay minerals and thus influenced by the primary microtexture and burial history of the sediment.

Temperature

So far no clear correlation has been found between the effect of temperature on thermal conductivity and water content and/or mineralogy.

Calculation of thermal conductivities by the geometric mean model

Based on the measured thermal conductivities, an attempt is made to calculate the conductivity of these sediments. In this study we will only consider the measured conductivity perpendicular to the layering at room temperature. The effect of anisotropy and temperature is therefore not included. The model is based on the geometric mean equation (1) where the conductivity of the matrix, k_s , is assumed to be a function of the mineralogical composition.

First an attempt is made to predict the thermal conductivity from the literature reported values of thermal conductivity of minerals (Table 1). The conductivity of matrix, k_s , is calculated with the geometric

mean equation from the estimated volumetric proportion of the minerals. The result of the calculated values is plotted versus the measured values (Fig. 7).

The plot shows no correlation between the measured and the predicted values where all predicted values are considerably higher than the measured values with a discrepancy up to 300%.

Then, to test if the geometric mean model based on mineralogical composition and water content is valid for these samples and the investigated data we used an inverse method. With a non-linear regression analysis the best fit geometric mean model was found from the data of measured thermal conductivity, mineralogy and water content. Thermal conductivity calculated with 'the best fit model' is plotted versus the measured thermal conductivities (Fig. 8) and the 'best fit conductivities' of the minerals of this model is shown in Table 3.

The 'best fit model' failed on three points: Firstly the plot on Fig. 8 and the regression coefficient ($R^2 = 0.04$), shows that there is bad correlation between the model and the measured thermal conductivities. Secondly the values of the conductivity of the minerals are of a magnitude lower than the literature reported values. Thirdly the variation of the conductivity of the minerals does not agree with values previous reported. As an example, smectite and illite have the highest conductivities in 'the best fit model'.

Conclusions

Thermal conductivities of argillaceous sediments from the Norwegian Continental Shelf are measured from 0.79

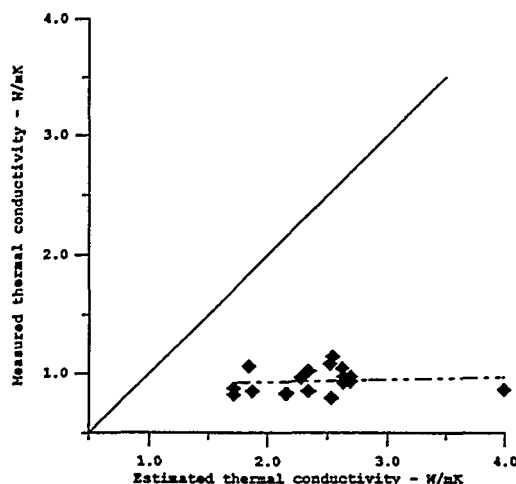


Fig. 7. Thermal conductivities measured versus calculated from literature values of conductivity of minerals.

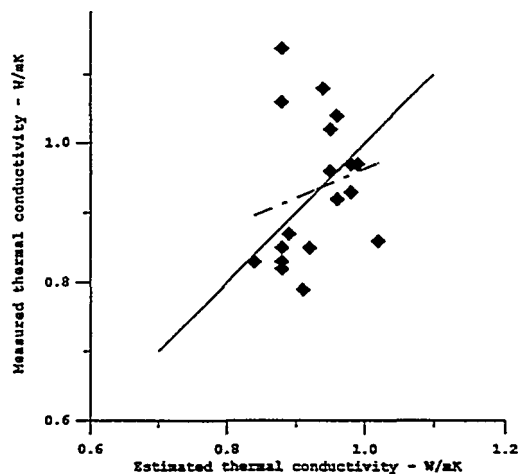


Fig. 8. Thermal conductivities calculated with 'the best fit geometric mean model' plotted against the measured values.

Table 3. The best fit values of thermal conductivity of the minerals

Minerals	Thermal conductivity (W/m K)
Quartz	1.01
Kaolinite	0.91
Chlorite	
Illite	1.42
Smectite	
I/S	
Pyrite	1.41
Feldspar	1.02
Carbonate	

to 1.14 W/m K. The thermal conductivity parallel to the layering is up to 1.70 higher than that perpendicular to the layering. The anisotropy effect may be of importance and taken into consideration when modelling in sedimentary basins with tilted strata.

The thermal conductivities presented in this work are lower than most data previously published. These earlier data have mainly been determined by needle probe techniques. The results are, however, comparable with thermal conductivities indirectly estimated from thermal studies of sedimentary basins (Blackwell & Steele 1989; Demongodin *et al.* 1991; C. Hermanrud 1993 pers. comm.).

The water content is found to have some influence of thermal conductivities. The mineralogy seems to be less important for the conductivity. An attempt to calculate thermal conductivities with the geometric mean model, from the water content and the mineralogy was not successful. An explanation may be that the mineralogical effect is lower for these fine grained sediments than for coarser samples.

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Paper 3

Paper 3

Thermal conductivity of selected clay- and mudstones from England*.

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ABSTRACT

The clay- and mudstones investigated in this study are London Clay, Fullers Earth, Oxford Clay and Kimmeridge Clay. Thermal conductivities of the samples were measured with a divided bar apparatus. The values measured perpendicular to layering ranged from 0.68 to 0.97 W/m·K. Comparative measurements of thermal conductivities were carried out by the needle probe method and Middleton's method. Deviation in the measured values up to 50% were obtained between the needle probe and the divided bar method. The measurements were compared with values of thermal conductivities estimated from the geometric mean model based on mineralogy and water content. These estimated values ranged from 0.87 to 2.01 W/m·K, which are considerably higher than the measured values. A correlation is found between the grain size distributions of the samples and the measured thermal conductivities. This textural effect on the thermal conductivity is assumed to be the main reason for the low measured values and the lack of correlation between the measured and the calculated values.

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INTRODUCTION.

Thermal conductivity is a physical property describing transfer of heat through the material. A knowledge of thermal conductivity is important in understanding and modelling of the temperature in sedimentary basins. Today there is still a lack of reliable information on sedimentary rocks, and especially for clays, claystones and shales there are uncertainties related to the determination of thermal conductivities (Blackwell & Steele, 1989; Brigaud & Vasseur, 1989; Demongodin et al., 1991; Midttømme et al., 1997a). Different methods are used to measure thermal conductivity, where the two main techniques are the stationary divided bar method and the transient needle probe method. Comparative measurements between the two methods are previously reported and agreement was obtained by Von Herzen & Maxwell (1959); Sass et al. (1971) and Brigaud & Vasseur (1989). Higher values of thermal conductivity were measured with the needle probe by Slusarchuk & Foulger (1973), Johansen (in Farouki, 1981), Somerton (1992) and Midttømme et al. (1997b.). The discrepancy in these studies is in the range of 10 - 20 %.

Special problems related to the measuring of thermal conductivities of clays, claystones and shales have resulted in less and probably poorer data available for these materials (Midttømme & Roaldset, 1997). The sampling and preparation of fine grained materials represents a major problem as the material easily breaks up in the sampling process and even if successfully cored the samples might be subjected to desiccation in laboratory conditions (Brigaud & Vasseur, 1989). The anisotropic structure, which is generally observed for fine grained sediments, might be considered as a source of error in the determination of thermal conductivity. The anisotropy of thermal conductivity is defined as the ratio between thermal conductivity parallel to the layering, k_{\parallel} , and the one perpendicular, k_{\perp} . An anisotropy of over 1.7 was measured for shales and clays (Penner, 1963; Prestholm & Fjeldskaar, 1993; Demongodin et al., 1993; Midttømme et al., 1997a). The measured anisotropy is probably affected by the methods of measurement and sample preparation. In the divided bar method the heat is transferred in a certain direction through the samples, while by the needle probe method the heat is more randomly transferred. In other methods the samples are ground to a fine powder before the conductivity is measured (Horai, 1971; Sass et al., 1971; Middleton, 1994). The effect of *in-situ* structure of the samples is not taken into account by these methods.

Models are developed to estimate thermal conductivity from other material properties. Porosity is considered to be of importance as pore fluids have lower thermal conductivity than the minerals (e.g., Gilliam & Morgan, 1987; Brigaud & Vasseur, 1989) (Table 1). A decrease in porosity will therefore increase the thermal conductivity. In the lack of reliable and simple methods of measuring the porosity,

water content and bulk density are used to describe the material quantitatively. Thermal conductivities of unconsolidated samples were estimated within an accuracy of 80 % of the measurements with a model based on the geometric mean model (Eq.1) with the water content (w) as an unknown parameter (Midttømme et al., 1997b).

$$k = k_w^w \cdot k_s^{(1-w)} \quad (\text{Eq.1})$$

- w - water content (volume of water content of sample volume),
 k_w - thermal conductivity of water (0.60 W/m·K),
 k_s - thermal conductivity of the matrix, (solid part of the sample).

Thermal conductivity is in more complex models related to mineralogy and porosity (Brigaud & Vasseur, 1989; Fjeldskaar et al., 1993; Middleton, 1994). These models are in some recently published studies not found to predict the thermal conductivity satisfactorily. Comparison between measured and estimated thermal conductivities for clays and shales shows poor correlation where the measured thermal conductivities are lower than the estimated values (Blackwell & Steele, 1989; Demongodin et al., 1991; Midttømme et al., 1997 a,b). Thermal conductivities of the main minerals in sedimentary rocks are listed in Table 1. Similar values are obtained by Brigaud & Vasseur (1989) and used in the basin modelling program, BMT, developed by Rogaland Research (Precede Users Guide, 1992).

Table 1. Thermal conductivities of common minerals in sedimentary rocks.
Determined from needle probe measurements carried out at room temperature (Horai, 1971).

Mineral	Thermal conductivity W/m·K
Quartz	7.8
Calcite	3.4
Dolomite	5.1
Anhydrite	6.4
Pyrite	19.2
Siderite	3.0
Orthoclase	2.3
Albite	2.3
Halite	6.5
Mica	2.3
Chlorite*	5.1
Kaolinite	2.8
Smectite (BMT)	1.8
Illite	1.8
Mixed layer I/S	1.9
Air	0.03
Water	0.60

*Chlorite: 3.3 W/m·K: Brigaud & Vasseur, 1989

The thermal conductivity is influenced by the texture of the material (e.g., Farouki, 1981; Brigaud & Vasseur, 1989) and this might be a reason for this poor correlation between measured and estimated thermal conductivities. The measured anisotropy of thermal conductivity is an example of this influence, where a considerable variation in thermal conductivity is measured due to the direction of heat flow through the material. Thermal conductivity is shown to depend on the grain size and grain size distribution, where coarse grained materials have higher thermal conductivity than finer material (Johansen, 1975; Beziat et al., 1992; Midttømme et al., 1997b.). From the conductivities presented in Table 2 (Blackwell & Steele, 1989), it seems obvious that the grain size has great influence on thermal conductivity.

Table 2. Thermal conductivities of sedimentary rocks at 20°C
(Blackwell & Steele, 1989).

Lithology	W/m·K
Claystone and siltstone	0.80 - 1.25
Shale	1.05 - 1.45
Sand	1.70 - 2.50
Sandstone	2.50 - 4.20

Beziat et al. (1992) found an increase in thermal conductivity with increasing content of sand in the samples. They assumed this effect was due to the contact resistance between the grains. The resistance decreases with increasing particle sizes as the number of contact points are reduced. In a study of unconsolidated clays from the Vøring Basin, offshore Norway, the effect of grain size fractions were found to have greater influence on the measured thermal conductivities than the mineralogy (Midttømme et al., 1997b).

Temperature and pressure are also found to influence thermal conductivity (e.g., Farouki, 1981; Brigaud et al., 1990). The effect of these factors are negligible in the present study as all measurements of thermal conductivities are carried out at nearly the same temperature and pressure.

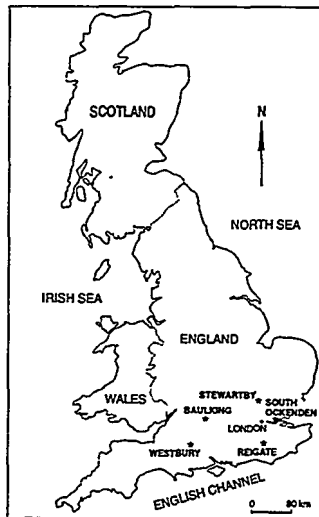


Figure 1. Map of the locations.

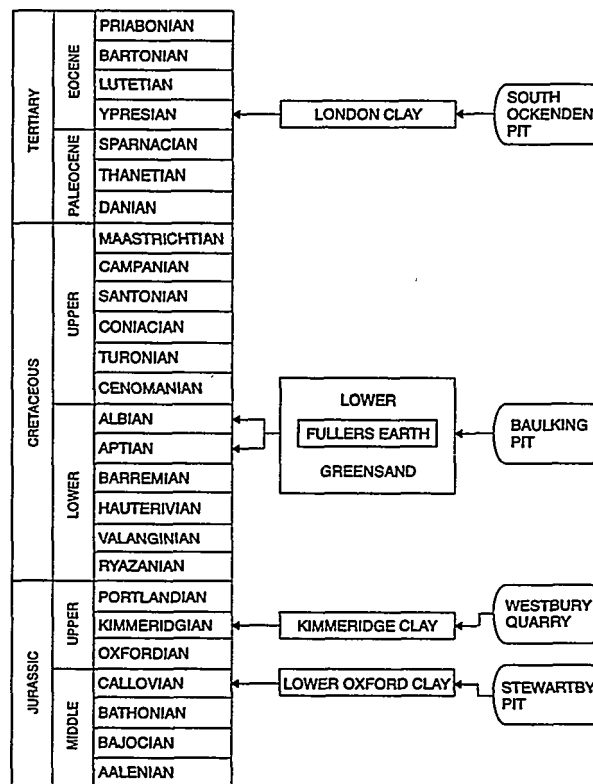


Figure 2. Stratigraphic position of the investigated clay- and mudstones.

GEOLOGICAL SETTINGS.

The claystones investigated in this study are London Clay, Fullers Earth, Oxford Clay and Kimmeridge Clay (Figures 1,2). These onshore clay- and mudstones are well known and their material properties have been extensively studied by Morris (1980), Huggett (1994), Kvilhaug (1995), Cartwright & Loneragan (1996) and others. The clay- and mudstones were sampled in co-operation with Imperial College, University of London in August 1992. The properties of these clay formations are of interest in basin modelling because of their equivalence to offshore North Sea clay- and mudstones sequences.

The four clay- and mudstones are briefly described below and their macro and micro texture is shown in Figure 3a-d. A more thorough description of the material is made in the report from the field work and sampling (Kvilhaug et al., 1993; Kvilhaug, 1995). Particular characteristics of the clay- and mudstones which might influence the thermal conductivity will be considered, in the following.

London Clay.

London Clay is a marine claystone of Eocene age which occurs as thick sequences in the Hampshire and London Basins (Sellwood & Sladen, 1981) (Figure 3a). The clay was sampled at South Ockenden pit, Essex, situated in the eastern part of the London Basin. The material can be characterized as a laminated silty claystone, where thin silt laminae separate a relatively homogenous looking clay. The distance between the silt laminae of this material is 5-20 cm. A detailed study of mineralogy and diagenesis of the London Clay from South Ockenden is given by Huggett (1994). The formation has been buried to a maximum of about 500 m, probably during the mid-Miocene tectonism which affected southern England (Huggett, 1994). The clay is slightly overconsolidated due to Quaternary glacial load (Kvilhaug et al., 1993).

Fullers Earth.

Fullers Earth is extreme in its composition by consisting mainly of Ca-smectite which is an alteration product from volcanic ash (Figure 3b). The material was collected at Baulking Pit in Oxfordshire. This clay is deposited as part of the Lower Greensand in Aptian-Albian time (Lower Cretaceous). The claystone is stiff and overconsolidated with no visible structures. The maximum burial depth is assumed to have been about 800 m (R. Marsden, pers. comm., 1992). Samples of Fullers Earth from Reigate, Surrey, (in the Weald Basin) were also obtained. This claystone has a rusty weathering hue, and seemed softer than the material from Baulking. However, other properties, such as texture, lack of

structures and colour, seem almost identical for the two sites (Kvilhaug et al., 1993). The maximum burial depth of this clay is estimated to 1000 m (R. Marsden, pers.comm. 1992).

Kimmeridge Clay.

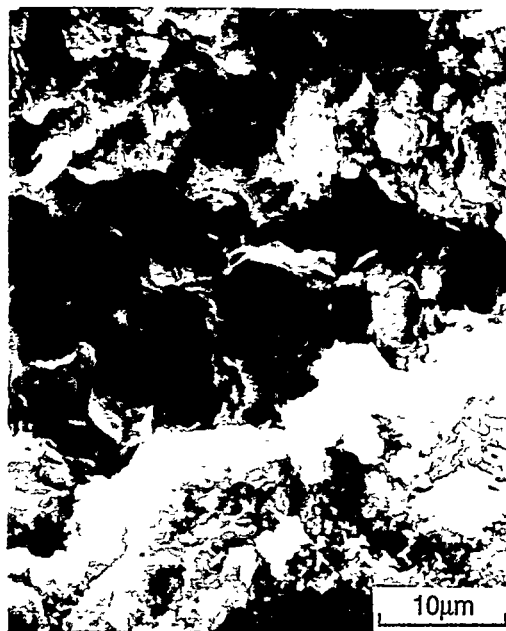
Kimmeridge Clay is an organic rich, calcareous mudstone of Kimmeridgian age (Late Jurassic) that crops out over large areas of southern and eastern England (Figure 3c). The Kimmeridge Clay, which is equivalent to Draupne Formation, are known as the main hydrocarbon source rocks in the Central and Northern North Sea (e.g., Grunau et al., 1986; Cornford, 1990). The material of Kimmeridge Clay was sampled at Westbury Quarry in Wiltshire. The material is a fissile mudstone with a well developed lamination and visible strings of silt. The shale is rich in fossils, mostly shells. The samples were taken from two different sites in the pit named A and B. The distance between the sites was about 100 m. The samples from B were more consolidated. According to R. Marsden (pers. comm., 1992), the material may have been buried to a depth of about 500 m.

Oxford Clay.

Lower Oxford Clay is an organic rich claystone of Callovian age (Middle Jurassic) that crops out over large areas of southern and eastern England (Morris, 1980) (Figure 3d). It is of similar age as the North Sea Heather Formation. It was sampled in Stewartby pit in Bedfordshire. The clay is rich in fossils, mostly ammonites. The material is poorly laminated. Thickness of the eroded overburden of the Oxford Clay is estimated to about 500 m (Jackson & Fookes, 1974).

Figure 3. Photographs and scanning electron microscopy micrographs of the clay-/ mudstones illustrating their macro- and micro texture. A) London Clay, B) Fullers Earth, (Note the contact to the overlying Lower Greensand). C) Kimmeridge Clay, D) Oxford Clay.

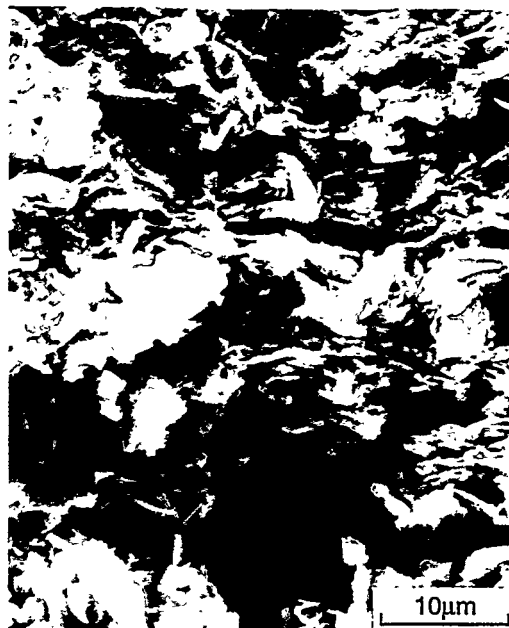
London Clay



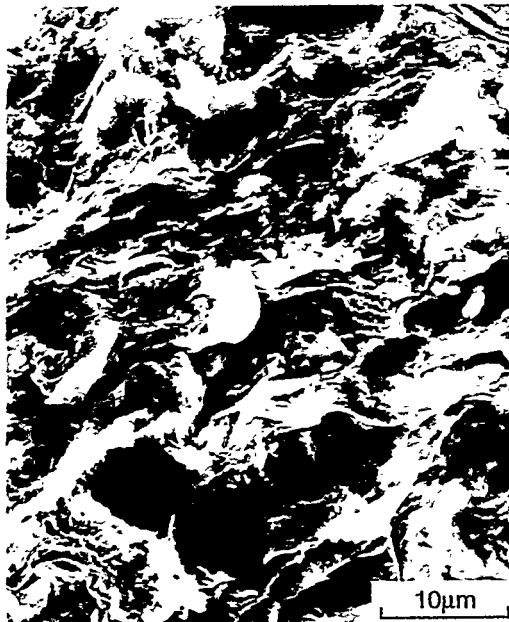
Fullers Earth



Kimmeridge Clay



Oxford Clay



PREVIOUS MEASUREMENTS OF THERMAL CONDUCTIVITIES.

Thermal conductivities of the four clay- and mudstones investigated in this study have been previously reported by Bloomer (1981) (Table 3). These measurements were carried out with the needle probe method and the divided bar apparatus on crushed samples by the method of Sass et al. (1971). Bloomer (1981) investigated 12 mudstones from central southern England. The variation in thermal conductivity was in the range 1.46 - 2.45 W/m·K, where the London Clay gave the highest values.

Table 3. Thermal conductivities measured by Bloomer (1981).

Sample	Lithology	Method	No. of values	Thermal conductivity W/m·K
London Clay	Sandy mudstone	NP ¹	5	2.45 ± 0.07
Kimmeridge Clay	Mudstone	NP/PB ²	58	1.51 ± 0.09
Oxford Clay	Mudstone	PB	11	1.57 ± 0.03
Fullers Earth	Mudstone	NP/PB	41	1.95 ± 0.05

¹Needle Probe measurement - The values of thermal conductivity are assumed to be the value parallel to the bedding (Bloomer, 1981).

²Phil box measurement (Sass method) (Sass et al., 1971) Divided bar measurements on crushed sample. The values obtained are assumed to be a mean value of perpendicular and parallel thermal conductivities.

METHODS.

Measurement of thermal conductivities.

Thermal conductivity was measured with a divided bar apparatus. This is a steady state method, where thermal conductivity is determined when the temperature gradient of the sample is constant and controlled. The apparatus used is developed at Department of Refrigeration Engineering, Norwegian University of Science and Technology, and is described in detail by Brendeng & Frivik (1974). Our measurements were carried out on water saturated cubes with sides of 3.0 cm. Tests show that because of the small size of the samples the measured values are up to 3.5 % lower than for bigger samples. Thermal conductivity was measured both perpendicular (k_{\perp}) and parallel (k_{\parallel}) to the layering.

The needle probe measurements were carried out at University of Aarhus, Denmark. This transient method was developed by Von Herzen & Maxwell (1959) and is today the most common laboratory method for measurement of thermal conductivity (Jessop, 1990). A probe, which contains a heating wire and a thermistor, is inserted into the material. When the system has attained temperature equilibrium, the temperature is recorded as a function of time. From this temperature-time curve the

thermal conductivity of the material can be determined (Jessop, 1990). Thermal conductivity parallel to the layering was measured by inserting the probe perpendicular to the layering. Thermal conductivity perpendicular to layering was calculated from the results of inserting the probe parallel and perpendicular to the layering (conf. Penner, 1963).

The third method, which is also a transient method has been developed by Middleton (1993) at Chalmers University, Sweden. The apparatus is similar to the divided bar apparatus where a constant heat flow is induced from the top of the sample, a block of size $4.0 \cdot 4.0 \text{ cm}^2$ and height 1.0 cm. The sample is insulated on all other surfaces. The temperature is measured at the base of the sample for about 60 seconds after introduction of the heat source (Middleton, 1993). Thermal conductivity can be estimated from the temperature-time plot from the similar equations as for the needle probe method.

Other laboratory investigations.

The mineralogical composition of the samples was determined by X-ray diffraction analysis (Brindley & Brown, 1980; Moore & Reynolds, 1989). The mineralogy was quantified by calculating the areas of the characteristic peaks and applying weighting factors developed for the XRD equipment at Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology by H.G. Rueslåtten. The quantification is considered to be semi-quantitative with average error in the order of 5-10 % (Rundberg, 1991).

The problem of porosity determinations in shales and claystones has among others been discussed by Truman et al. (1989). With reference to some of the discussion by him and others, porosity was determined by weighing water saturated samples of known volume before and after drying at 40 °C for two weeks and then recalculate the water loss to water volume (i.e. porosity). By this method the "free water" which also may be considered as a measure for the "effective porosity" is determined. This method is not any standard method, but from laboratory investigations of smectitic samples carried out at this Department the transformation to illite has for some samples started at temperatures above 40 °C. Bound water is, by the definition of porosity (North, 1985) not included either in the effective or the total porosities. Total water content was calculated from weight reduction after drying for 3 days at 105 °C.

The densities were measured with a pycnometer. Bulk density was calculated from data by a manual pycnometer, and grain density was measured with a AccuPyc 1330 Pycnometer.

The grain size distribution was determined by separating the material coarser than 63 μm by sieving and by analysing the fraction finer than 63 μm by Sedigraph.

Table 4. Comparison measurements of thermal conductivity.

Sample	Thermal conductivity, perpendicular (W/m·K)			Thermal conductivity, parallel (W/m·K)		
	Divided bar	Needle probe ^a	Middleton's method	Divided bar	Needle probe ^a	Middleton's method
London Clay	0,83	0,84 (1)		1,19	0,94 (3)	
Fullers Earth	0,68	0,73 (3)		0,80	0,98 (1)	
Kimmeridge Clay	0,97	1,21 (1)	0,89/0,96	1,20	1,21 (1)	1,18/1,07
Oxford Clay	0,79	1,19 (2)	0,84	1,11	1,29 (3)	1,11

^a The number in parenthesis gives the quality of the measurements, 1 is good and 3 is poor.

Table 5. Thermal conductivities measured with divided bar apparatus.

Clay- and mudstone.	Sample	Thermal conductivity perpendicular k_{\perp} [W/m·K]	Thermal conductivity parallel k_{\parallel} [W/m·K]	Anisotropy effect $a=k_{\parallel}/k_{\perp}$
London Clay	L1	0.82	1.15	1.40
	L2	0.83	1.23	1.48
Fullers Earth, Baulking	F1	0.71	0.81	1.13
	F2	0.68	0.82	1.20
	F3	0.66	0.77	1.16
Fullers Earth, Reigate	R1	0.74	1.09	1.47
	R2	0.76	0.81	1.07
	R3	0.74	0.77	1.04
Kimmeridge Clay	K1A	0.96	1.20	1.25
	K2A	0.97	1.20	1.23
	K3B	0.70	1.22	1.74
	K4B	0.68	1.18	1.72
Oxford Clay	O1	0.84	1.11	1.32
	O2	0.76	1.11	1.46
	O3	0.75	1.11	1.49

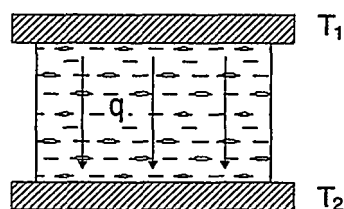
COMPARISONS OF THERMAL CONDUCTIVITY MEASUREMENTS.

All measurements of thermal conductivities presented in this study (Tables 4, 5) are lower than the measurements carried out by Bloomer (Table 3). Bloomer's measurements for London Clay and Fullers Earth appear to be more than twice as high as the measurements carried out in this study. The discrepancy in the measurements for Fullers Earth is most disquieting since this clay appears to be nearly homogenous and isotropic. The discrepancy can therefore hardly be due to mineralogical nor textural variations of the measured samples. London Clay was by Bloomer classified as sandy mudstone. Our measurements were carried out on a claystone with a content of silt and sand of 30% and 10% respectively. Lithological differences between the samples analysed might thus be a reason for this discrepancy. Regarding this comparison, it is noteworthy that the measurements by Bloomer (1981) and the University of Aarhus were both carried out by the needle probe method (see Tables 3, 4). The discrepancy between these results shows that there might be considerable disagreement in measurements carried out by the same method.

For the samples investigated in the present study there are also some disagreements in the comparative measurements of the three methods (Table 4). The measurements with the method developed by Middleton (1993) and the divided bar apparatus are in good agreement, while in general the needle probe method gives higher values. Of the eight measurements, the needle probe gives higher thermal conductivity for five of the samples (+7 % - +51 %) and lower for the parallel measurements of London Clay (-21%). Two of the measurements are in agreement (+1 %). It is difficult from these comparative measurements, because of the variation and also the limitation of measurements, to confirm if there is methodical discrepancy between the two methods as previously suggested by Slusarchuk & Foulger (1973); Farouki (1981) and Midttømme et al. (1997b). The measurements perpendicular to the layering for the organic rich Kimmeridge Clay and Oxford Clay show the highest deviation between the needle probe and the two other methods (Table 4). Thermal conductivity measured parallel to the layering for these two clays, and particular for the Kimmeridge Clay, are in good agreement. The results of the measurements on the organic rich clays give a low or no anisotropy of the thermal conductivity by the needle probe methods, while a considerable anisotropy is measured by the two other methods. A high content of fossil and shell debris with a clear orientation parallel to the layering were easily seen in these two mudstones. The needle probe method differs from the other methods in the way the heat is transferred through the sample. By this method the heat is transferred radially from a probe inserted into the sample. For the apparatus developed by Middleton, and the divided bar apparatus, the heat is transferred from a slab through the sample (Figure 4). In the divided

bar method great emphasis is made to obtain controlled and stationary conditions of the heat flow through the samples. The shell and fossil debris, with preferred orientation in the two organic rich clays might be an explanation of the deviation in the perpendicular measurements with the needle probe method. Because the heat flow is radiated from a line source, the fossil and shell debris might also strongly influence the thermal conductivity measured perpendicular to the layering. This influence might also explain the lack of anisotropy of the measured conductivities for the organic rich clays carried out with this method.

Divided bar method



Needle probe method

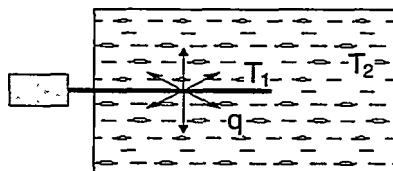


Figure 4. Heat flow through the samples during the thermal conductivity measurements. T_1 and T_2 designate the high and low temperature, while q represents the heat flow indicated by the arrows.

THE EFFECT OF MATERIAL PARAMETERS ON THE THERMAL CONDUCTIVITY.

Two or three samples of each of the clays- and mudstones were prepared and measured with the divided bar apparatus. The thermal conductivity was measured on water saturated samples both perpendicular and parallel to the layering, as shown in Table 5. The mineralogical composition and the physical properties of the material are shown in Tables 6 and 7. In sedimentary basins the dominating heat mechanism is the conductive heat transferred from the Earth's interior through the crust. For this reason the perpendicular values of the thermal conductivities measured and are used in the following. This measured thermal conductivities varies in the range of 0.66 W/m·K to 0.97 W/m·K for the samples of the four clay- and mudstones. These values of thermal conductivities will be correlated with the mineralogical, physical and textural properties of the samples, and the influence of these properties on the thermal conductivity will be discussed.

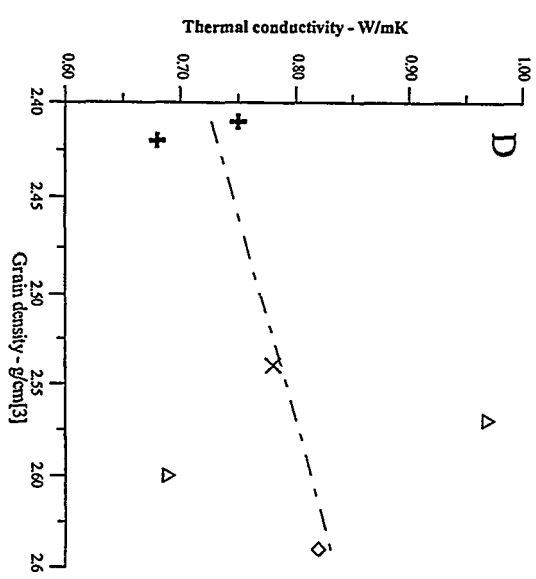
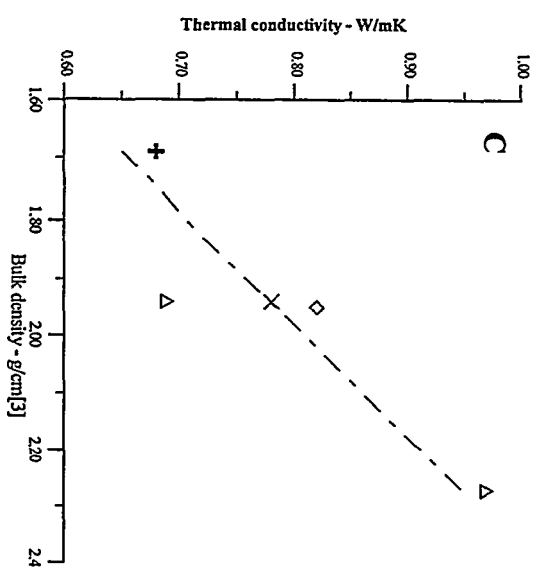
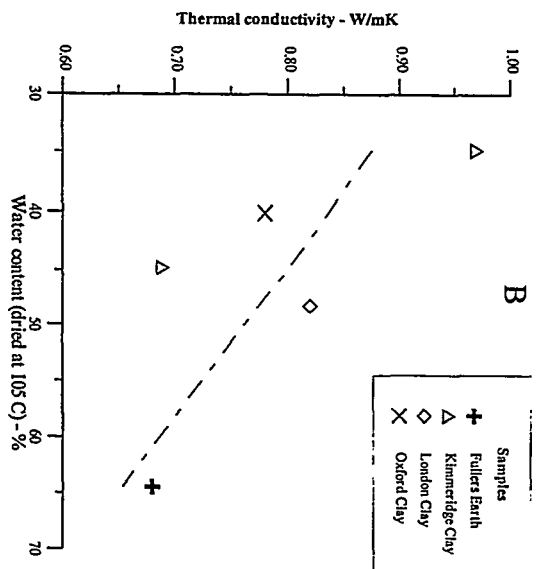
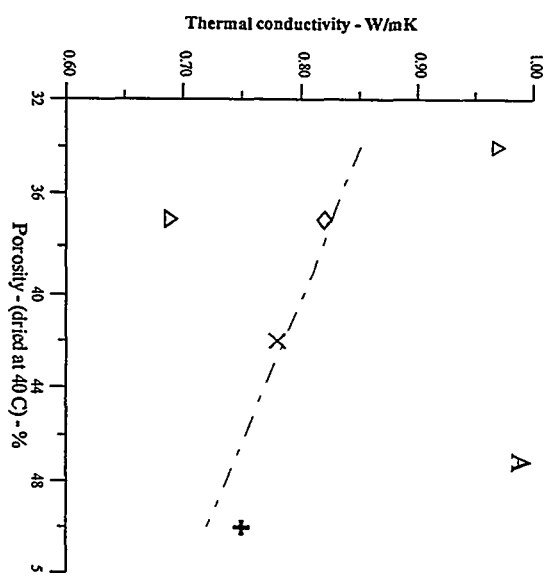
Table 6. Mineralogy of the samples.

Sample	Quartz	Pyrite	Feldspar	Calcite	Dolom	Siderite	Gypsum	Aragon	Kaolin.	Illite	Smect.	I/S
London Clay	37	2	18		2				13	16	5	7
Fullers Earth, Baulking			2			3					95	
Fullers Earth, Reigate			2			3					95	
Kimmeridge Clay, A	18	2	3	62			2	4	4	6		
Kimmeridge Clay, B	42	11	7	5			2		8	13		14
Oxford Clay	34	9	6	16					13	22		

Table 7. Densities, porosity, water content and grain size fractions of the samples.

Sample	Grain density g/cm ³	Bulk density g/cm ³	Porosity % of volume	Water content % of volume	Clay fraction % of weight	Silt fraction % of weight	Sand fraction % of weight
London Clay	2.64	1.95	37	48	58	33	9
Fullers Earth, Baulking	2.42	1.69		65	85	15	-
Fullers Earth, Reigate	2.41		50		85	15	-
Kimmeridge Clay, A	2.57	2.27	34	35	44	40	16
Kimmeridge Clay, B	2.60	1.94	37	45	65	34	1
Oxford Clay	2.54	1.94	42	40	44	46	10

Figure 5. Thermal conductivity plotted versus: a) porosity, b) water content, c) bulk and d) grain densities. The linear regression lines are shown.



The effect of porosity, water content and densities on thermal conductivity.

Thermal conductivity is plotted versus porosity, water content, bulk and grain densities in Figure 5a-d. Since water has lower thermal conductivity than the minerals, a decrease in the measured thermal conductivities with increasing porosity of the samples is expected. This trend is clearly seen in Figure 5a. Because of a high content of clay minerals in these samples, water will occur not only in the pores but also as interlayer, or bounded water, within the lattice spaces of expandable clays. This water will certainly also have the effect of lowering the thermal conductivity. For Fullers Earth, consisting of nearly pure smectite, the water content is measured 30 % higher than the porosity. For all four clay- and mudstones the water content seems to fit the variation in the measured thermal conductivity better than the porosity. The measured thermal conductivities of the two samples of Kimmeridge Clay are reflected by the variation in water content. There is no variation in the measured porosity of these samples.

In some studies there seems to be a confusion between the porosity and the water content (Robertson, 1979; Morin & Silva, 1986; Brigaud & Vasseur, 1989; Demongodin et al., 1991), and also of the different types of 'porosities', effective or total (e.g., Griffiths et al., 1992). Such confusion will probably be a source of error in estimating thermal conductivity, since the porosity is considered as an important parameter in many models. A more consistent use of this parameters will certainly improve the estimation of thermal conductivity.

Densities, both bulk and grain density, are often used as parameters in modelling thermal conductivity of sedimentary rocks (Penner, 1962; Horai, 1971; Johansen, 1975; Farouki, 1981; Poulsen et al., 1981). Thermal conductivity plotted against bulk density and grain density (Figure 5c,d) show a clear trend between the bulk densities and the measured thermal conductivities. The variation in bulk density, which is controlled both by the mineralogy and the porosity, seems to correlate with the measured thermal conductivity. This same effect will also be taken into account when using the porosity or water content as a parameter. There is no clear trend between the grain density and the measured thermal conductivity.

The effect of mineralogy.

Thermal conductivities of these clays were estimated by the geometric mean model from the mineralogy and water content. The mineral conductivities listed in Table 1 were used in the calculation. The estimated thermal conductivities are plotted against the measured ones in Figure 6.

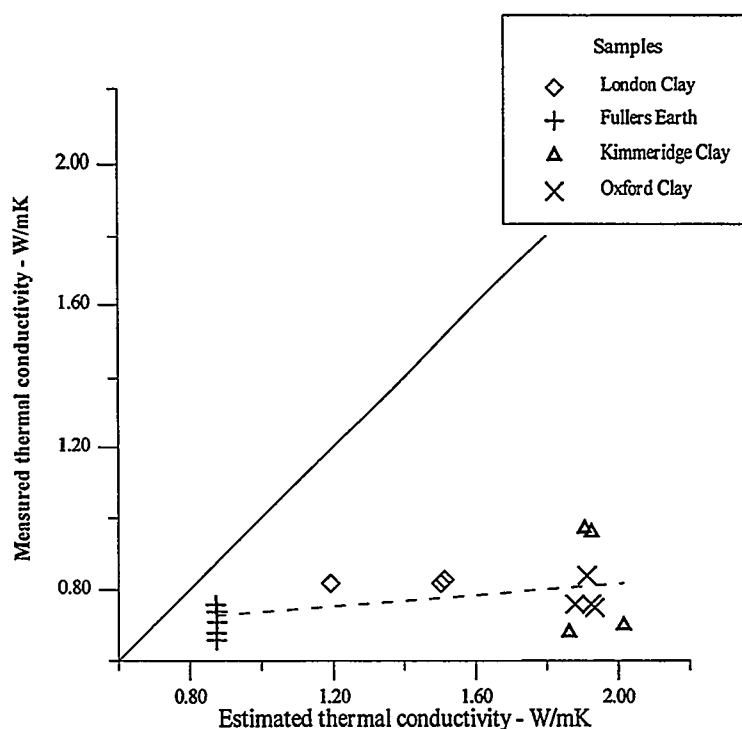


Figure 6. Calculated thermal conductivity versus measured thermal conductivity. The solid line is the unity line (1:1). The dotted line is the regression line.

If the measurements of thermal conductivities are correct, this mineralogical model fails to estimate the thermal conductivity of these samples. As seen in Figure 6, the estimated thermal conductivities for all of the samples are considerably higher than the measured values. The value of the thermal conductivity of the Kimmeridge Clay is an example of the lack of correlation with the mineralogy. Of the minerals present, pyrite and quartz have high thermal conductivity (Table 1). Samples with a high content of these minerals are expected to have higher thermal conductivity. The sample from site A has a content of quartz and pyrite of 18 and 2 % respectively, while the sample from site B has a quartz content of 44 % and a pyrite content of 11 %. From the mineralogy the thermal conductivity of sample B is predicted to be higher than that of sample A. The measurements however show the opposite, as the thermal conductivity of sample A is 40 % higher than of the sample B, 0.97 W/m·K and 0.69 W/m·K respectively.

A thermal conductivity of 0.68 W/m·K is measured for Fullers Earth. This value is only 13 % higher than for pure water. Because of the homogeneity of this clay there is low uncertainty related to the determination of the mineralogy. The mineral conductivity of smectite is 1.8 W/m·K (Table 1). To calculate a bulk thermal conductivity of 0.68 W/m·K with the geometric mean model (Eq.1), the matrix conductivity of Fullers Earth is estimated to 0.77 W/m·K or 0.86 W/m·K if the bounded water is excluded. A possible explanation for the lack of correlation between the measured thermal conductivities and the mineralogy for Fullers Earth is that the mineral conductivity of this authigenic formed Ca- smectite is much lower than the values previously reported for smectite.

Another explanation for these low values measured on Fullers Earth, and also for the three other clays, is that there are other material parameters in addition to mineralogy which have strong influence on the thermal conductivities of these samples.

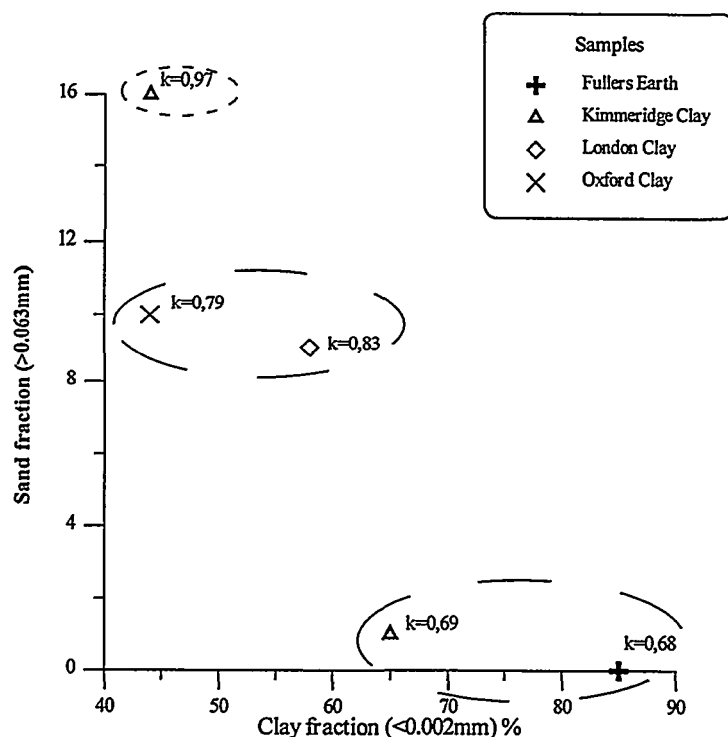


Figure 7. The clay fraction (<2 μ m) of the samples plotted versus the sand fraction (>63 μ m). The measured thermal conductivity is shown.

The effect of grain size distribution.

The sand fraction ($>63\ \mu\text{m}$) of the samples is plotted against the clay fraction ($<2\ \mu\text{m}$) (Figure 7). The clay- and mudstones fall into three groups, one group with the samples with highest clay contents which give the lowest thermal conductivities, another group with the samples with high clay and sand content which give intermediate conductivities, and a third group with the highest sand content which give the highest conductivities. The sand fraction thus seems from this plot to have a strong influence on the measured thermal conductivity of these samples.

A strong influence of the grain size distribution on the thermal conductivities might explain the low measured thermal conductivities obtained and the lack of correlation with the mineralogy. The very low thermal conductivities, only 15 % higher than pure water, obtained for Fullers Earth and Kimmeridge Clay B may possibly be explained by the very fine-grained size distribution of these samples. A high influence of the sand content on thermal conductivity for these fine-grained samples can explain the variation in the thermal conductivities of Kimmeridge Clay: the sample with a sand content of 16 % has 40 % higher thermal conductivity than the sample with 1 % sand, 0.97 and 0.69 W/m·K respectively.

The anisotropy of thermal conductivity.

The anisotropy of the measured thermal conductivities ($a=k_{\text{II}}/k_{\text{I}}$) are in the range of 1.04 to 1.74 (Table 5). The content of clay minerals and the burial history of the clay- and mudstones are factors that are assumed to influence the anisotropy of the thermal conductivity (e.g., Midttømme et al., 1997a). The clay minerals are anisotropic and these minerals will become even better orientated with increasing depth. An increase in anisotropy with increasing content of clay minerals and burial depth is therefore expected (Demongodin et al., 1993). The results show, however, that the Fullers Earth, which consists of 95 % smectite and has been buried deepest, has the lowest anisotropy. The SEM micrograph of Fullers Earth (Figure 3b) shows a homogeneous texture. Since this clay is authigenically formed with a special texture, this sample might be considered as an exceptional case. There is no clear trend between the anisotropy and the clay mineral content and the burial depth when considering the other clays. The variation of the anisotropy of Kimmeridge Clay A and B (Table 5) is also of interest because these samples have the same burial history. Sample B has a higher content of clay minerals than sample A, and this may cause the variation in the measured anisotropy. The variation in anisotropy for Kimmeridge Clay is due to the variation in perpendicular measured thermal conductivity, since there is no variation in thermal conductivity measured parallel to the layering. As

previously suggested the very low perpendicular thermal conductivity measured for Kimmeridge Clay B might be due to the very fine grain size distribution of this sample. The fact that there is low variation in the parallel measurements for both the organic-rich clays, Kimmeridge Clay and Oxford Clay, suggests that the organic material has a strong effect on the thermal conductivity. The strong anisotropic effect measured on the samples from site B of Kimmeridge Clay is therefore assumed to be due to textural effects, in this case due to a very fine grain size distribution and a high content of organic material parallel to the bedding.

CONCLUSIONS.

Thermal conductivities measured on four selected clay- and mudstones with the divided bar apparatus are in the range of 0.66 W/m·K to 0.97 W/m·K. These results are lower than previous measurements on these clays by Bloomer (1981). The grain size distribution of the samples shows a good correlation with the measured thermal conductivities as the sample with the highest sand content has the highest thermal conductivity, and samples with highest clay contents have lowest thermal conductivities. Correlation is also observed between the thermal conductivities and porosity, water content, and bulk density. The water content seems to reflect the variations in the measured conductivities better than the porosity. No clear trend could be observed between the grain density and thermal conductivity.

Comparative measurements carried out with the needle probe method and the method developed by Middleton, demonstrated some disagreements between the needle probe method and the two other methods. For the organic rich mudstones this discrepancy in the measurements is suggested to reflect methodical variation in the direction of heat flow through the sample during measurement.

Thermal conductivities of the clay- and mudstones, estimated by the geometric mean model from water content and mineralogy, were considerably higher than the measured values. The very fine grained nature of these clay- and mudstones are assumed to be the reason for the extremely low measured thermal conductivities, and the lack of correlation with the mineralogically based model.

ACKNOWLEDGEMENTS.

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Paper 4

Paper 4

Thermal conductivity of unconsolidated sediments from the Vøring Basin, Norwegian Sea.*

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ABSTRACT

Thermal conductivities of 103 samples of unconsolidated sediments from the Vøring Basin, Norwegian Sea, were measured with the needle probe technique. The measured thermal conductivities ranged from 0.69 to 1.57 W/m·K. Comparative measurements of 11 of the samples were carried out with a divided bar apparatus. These measurements gave uniformly lower values than the needle probe measurements, however, sample to sample differences were largely preserved. A systematic calibration deviation is assumed to be the main reason for the disagreement. Thermal conductivities were also estimated by two accepted models, one based on the quartz content and one based on the total mineralogical composition. Both models estimated higher values than the measured ones. Based on the geometric mean model, new models to estimate thermal conductivities of unconsolidated sediments were proposed and tested. For these sediments, water content was found to be the main factor controlling the thermal conductivity, and thus a fairly good estimate of thermal conductivity can be made directly from the measurements of water content ($R^2 = 0.81$). Grain size fraction, and especially the coarsest fraction ($>63\mu\text{m}$), strongly influence thermal conductivity, and is for these sediments a more important factor than the total mineralogy. The best fit model ($R^2=0.88$) was obtained when predicting thermal conductivity from a combination of water content, grain size fractions and the mineralogy. A simpler model only depending on the coarsest grain size fraction ($>63\mu\text{m}$), and the water content had nearly an equal good quality ($R^2=0.88$). This is suggested to be the preferable model for thermal conductivity of unconsolidated sediments.

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INTRODUCTION.

Thermal conductivity is a physical property governing the transfer of heat through materials. This parameter is of major importance for understanding the present and past thermal regimes within sedimentary basins and for modeling the temperature dependent physical and chemical processes within sedimentary basins. Thermal conductivity can be determined by laboratory measurements or calculated from other known physical properties. Measurements of thermal conductivities of sedimentary rocks show variations in the range of 0.4 - 6.5 W/m·K (Clark, 1966; Gilliam & Morgan, 1987; Schön, 1996). For basin modeling purposes thermal conductivities, in general, have to be estimated. Many models, both physical and empirical, to estimate thermal conductivity have been published. Overviews of existing models are reported in among others Johansen (1975), Farouki (1982), Zimmerman (1989) and Midttømme et al. (1994). Factors influencing thermal conductivity are porosity, pore filling material, mineralogy, grain size, fabric, temperature and pressure (Brigaud et al., 1990; Somerton, 1992, Midttømme et al, 1994). The uncertainty is, however, to what extent each of the parameters affects the thermal conductivity (e.g. Hermanrud, 1993).

Measurement of thermal conductivity.

Measurements of thermal conductivity are the basis for developing models of thermal conductivity in sedimentary basins. Today there are few published thermal conductivity measurements where detailed rock description is included (McKenna et al., 1996). Another point of uncertainty is the reliability of many of the methods and measurements of thermal conductivity that have been published. Different methods are used, where the two main techniques are the stationary divided bar method and the transient needle probe method. The divided bar apparatus is considered as the most exact method (Johansen, 1975; Farouki, 1981; Brigaud et al., 1990), and is recommended by the International Heat Flow Commission wherever possible for competent cores (Beck, 1988). The needle probe method, on the other hand, is easier and more rapid, and less demands are made on sample preparation. The needle probe method is the most widely applied method for measuring thermal conductivity of deep sea sediments (Kasameyer et al., 1972; Morin & Silva, 1984; Matsuda & Von Herzen, 1986) since the measurements can by this technique be done onboard ship.

Comparative measurements between the two methods are previously reported and agreement was obtained by Von Herzen & Maxwell (1959), Sass et al. (1971) and Brigaud & Vasseur (1989). Higher

values of thermal conductivity were measured with the needle probe by Penner (1963); Slusarchuk & Foulger (1973), Johansen, Norwegian University of Science and Technology, (unpublished, ref. in Farouki, 1981) and Somerton (1992). The discrepancy in these studies is in the range of 10-20 %.

Models of thermal conductivity.

Models of thermal conductivity of sedimentary rocks are of three general types (Somerton, 1992) 1) mixing law models, which combine values of the thermal conductivity of the rock matrix (k_s) with the conductivity of the pore fluid (k_f) on the basis of porosity 2) empirical models in which thermal conductivity is related to easily measured physical parameters and to laboratory data, and 3) theoretical models based on heat transfer theory for simplified geometries. Preferably, one would use a theoretical model to describe the physics of heat conduction (Zimmerman, 1989; Somerton, 1992), but sufficiently reliable models have not yet been developed, and empirical modifications of the equations are needed. Empirical models, however, may not be applicable to other rock types or in other geographic areas (McKenna et al., 1996). There is for example a basic difference in the thermal characteristics of consolidated and unconsolidated rocks (Somerton, 1992).

One of the most successful of the mixing law models is given by the statistical expression, geometric mean (Equation 1).

$$k = k_f^\phi \cdot k_s^{(1-\phi)} \quad (1)$$

k	-	thermal conductivity of the sediment (W/m·K),
k_f	-	thermal conductivity of the pore fluid (W/m·K),
k_s	-	thermal conductivity of the matrix (the solid part of the sediments) (W/m·K),
ϕ	-	porosity (0.00 -1.00).

This model is among others used by Woodside & Messmer (1961), Sass et al. (1971), Balling et al. (1981), Brigaud et al. (1990) and McKenna et al. (1996). This simple multiplicative mixing law model is in many cases found to be better than more sophisticated models to calculate the thermal conductivity of sediments (Demongodin et al., 1991). Two additive mixing law models expressed by the arithmetic (Equation 2) and harmonic mean (Equation 3) are also widely used (Vacquier et al., 1988; Somerton, 1992; Pribnow & Umsonst, 1993; McKenna et al., 1996). These models are based on respectively parallel and serial arrangement of the components relative to the direction of heat flow.

$$k = \phi k_f + (1 - \phi) k_s \quad (2)$$

$$\frac{1}{k} = \frac{\phi}{k_f} + \frac{(1 - \phi)}{k_s} \quad (3)$$

The values estimated by these models are considered to give the boundary values of thermal conductivity of the material. For more isotropic samples the geometric mean model, which predicts a mean value of the arithmetic and harmonic means, would theoretically be more correct. The application of these three mixing law models is more thoroughly discussed by Schön (1996) and Midttømme & Roaldset (in press.).

Porosity - ϕ

The porosity is a well-known parameter, although not so easy to determine accurately. Porosity can be determined either from laboratory measurements, well-log data or from porosity models. The effect of porosity on thermal conductivity and the confusion according the different types of porosities e.g. effective and total porosities and water content are discussed by Griffiths et al. (1992) and Midttømme et al. (1997a).

Thermal conductivity of fluid - k_f

Thermal conductivity of the fluid (k_f) depends on the fluid composition (Somerton, 1992; Jensen & Doré, 1993). Sedimentary rocks are in general saturated with water, and the thermal conductivity of water ($k_w = 0.60$ W/m·K) is used as a constant in many models of thermal conductivity (Horai, 1971, Brigaud et al., 1990; Demongodin et al., 1991). Values of conductivity used for hydrocarbon pore fluids are for gas: $k_{gas} = 0.079$ W/m·K and for oil: $k_{oil} = 0.209$ W/m·K (Jensen & Doré, 1993). The low thermal conductivity of air ($k_{air} = 0.024$ W/m·K) is a problem in laboratory measurement, since a replacement of water by air will have large influence on the measured thermal conductivity.

Thermal conductivity of matrix - k_s

The main difficulty with the geometric mean model lies in how to model the matrix thermal conductivity (k_s). The matrix thermal conductivity is a complex parameter depending on mineralogy and textural factors. There seems to be two main methods to estimate matrix conductivity 1) from

mineralogy and 2) from lithology. The matrix thermal conductivity is estimated by the geometric mean model (Equation 4) using; 1) lithology data interpreted from logs (Brigaud et al., 1990; Demongodin et al., 1991; Vik & Hermanrud, 1993) or 2) mineralogical data estimated from laboratory investigations (Brigaud & Vasseur, 1989; Brigaud et al., 1990; Fjeldskaar et al., 1993; Middleton, 1994; Midttømme et al., 1997b).

$$k_s = \prod_{i=1}^n k_i^{V_i} \quad (4)$$

- i - mineral or lithology component,
- k_i - thermal conductivity of i ,
- V_i - volume of i .

Estimates of thermal conductivity for basin modelling purposes are in most cases based on lithologic information. This determination is at the best semi-quantitative and may result in standard deviations of the estimated thermal conductivities of 20 % or more (Hermanrud, 1993). The modeling based on mineralogy is considered to be more exact, with a standard deviation between predicted and measured values to 10-15 % (Brigaud et al., 1990). Mineralogical models require detailed information on the mineralogy of the material.

Thermal conductivities of pure minerals and well-defined lithologies are listed in Tables 1 and 2. Models based on partial mineralogies have been successfully attempted. For example, because of the high mineral conductivity of quartz, the quartz content is considered an important parameter. Hence models with the quartz content as the major factor influencing conductivity have been proposed for crystalline rocks (Birch & Clark, 1940), sediments (Johansen, 1975) and sedimentary rocks (Robertson, 1979).

Thermal conductivities of deep sea sediments have been estimated with the geometric mean model based on the contents of CaCO_3 and SiO_2 (Matsuda & Von Herzen, 1986). In another study of deep sea sediments, the high conductivities measured on some of the samples were related to a high content of calcite in these samples (Horai & Von Herzen, 1985). The mineral conductivity of this biogenic pelagic calcium carbonate was by best fitting linear relationship determined to be 4.5 W/m·K.

Table 1. Thermal conductivity of common minerals in sedimentary rocks (Horai, 1971). Determined from needle probe measurements carried out at temperatures in the range of 15 to 30 °C and standard pressure.

Mineral	Thermal conductivity W/m·K
Quartz	7.8
Calcite	3.4
Dolomite	5.1
Anhydrite	6.4
Pyrite	19.2
Siderite	3.0
K-feldspar	2.3
Albite	2.3
Mica	2.3
Halite	6.5
Kaolinite	2.8
Illite	1.8
Mixed layer I/S	1.9

Table 2. Thermal conductivity of selected rocks at 20 °C (Blackwell & Steele, 1989).

Lithology	Thermal conductivity W/m·K
Clay-/siltstone	0.80-1.25
Shale	1.05-1.45
Sandstone	2.50-4.20
Limestone	2.50 -3.10

The content of clay minerals is found to lower the matrix conductivity (Robertson, 1979; Gilliam & Morgan, 1989; Midttømme et al., 1994b; McKenna et al., 1996). These minerals are also considered as a point of uncertainty in both measurements and estimates of thermal conductivities (McKenna et al., 1996; Midttømme & Roaldset, 1997). Mudrock cores are rarely collected, and when samples are available, they are typically desiccated, fractured and fragile (Brigaud & Vasseur, 1989, McKenna et al., 1996). Special physical and chemical properties of the clay minerals will complicate the modeling of the heat transfer through clayey material (Midttømme & Roaldset, 1997). Since a large specific surface area is characteristic of clay minerals, a correlation between the external surface area and the degree of contact resistance to heat flow through these materials can be expected (Farouki, 1981). Adsorption and exchange of water and other molecules will occur on external and internal surfaces and influence the thermal conductivity (Farouki, 1981). An anisotropic structure is another characteristic of the clay minerals. Higher thermal conductivity is often measured parallel (k_{\parallel}) to the layering than

perpendicular (k_{\perp}). The measured anisotropy of thermal conductivity of muds and mudrocks ($a = k_{\parallel}/k_{\perp}$) is often found to be considerable (Penner, 1963; Gilliam & Morgan, 1987; Prestholm & Fjeldskaar, 1993; Midttømme et al., 1997a), even on material with no visible layering (Midttømme et al., 1997b). The anisotropy is explained by the flaky shape of the clay minerals, and the orientation of these particles during deposition and burial (Demongodin et al., 1993). Measurements on mica for example show an anisotropy of ten (Goldsmid & Bowley, 1960). Other structural effects caused by the clay minerals are also found to influence the thermal conductivity. Penner (1963) related thermal conductivity of allogenic clays to their depositional environments. Higher thermal conductivities were measured for flocculated marine clays than for dispersed clays formed in fresh water, while a considerably higher anisotropy of thermal conductivity was measured for the lacustrine clays which are often finely laminated.

Temperature effect on thermal conductivity.

Variation in temperature will induce changes in the thermal conductivity of sedimentary rocks (Anand et al., 1973; Balling et al., 1981; Gilliam & Morgan, 1987; Demongodin et al., 1993; Midttømme et al., 1997b). A slight increase in thermal conductivity of clays and shales has been observed in the temperature range from 0 °C to 90 °C by Anand et al. (1973), Morin & Silva (1984), Gilliam & Morgan (1987) and Somerton (1992), whereas a decrease was measured by Balling et al. (1981), Brigaud et al. (1990) and Demongodin et al. (1991). Measurements show that thermal conductivity of water increases with increasing temperature, while thermal conductivity of most of the minerals decreases with increasing temperature (Clark, 1966; Balling et al., 1981; Demongodin et al., 1993). Therefore the thermal conductivity of water saturated rocks can vary widely depending upon the proportion of water to the solid part of the matrix.

SAMPLES.

Samples of unconsolidated marine sediments from the Vøring Basin, Norwegian Sea were investigated (Figure 1). This area was opened for petroleum exploration in 1995. As part of the Ocean Drilling Program (Eldholm et al., 1987, 1989), an extensive study of deep sea sediments from Vøring Basin has previously been reported.

The samples in this study were obtained via gravity coring by IKU Petroleum Research in the summer of 1994. A total of 103 samples from 41 sites was included. The core depths range from 0.15 m to 3.50 m below sea bottom at water depths near 1500 m. The samples are soft marine sediments with a considerable position of terrigenous derived materials. Shells and organic debris were common and occasional ice rafted dropstones of gravel size were detected. No lamination or other visible textures could be detected.

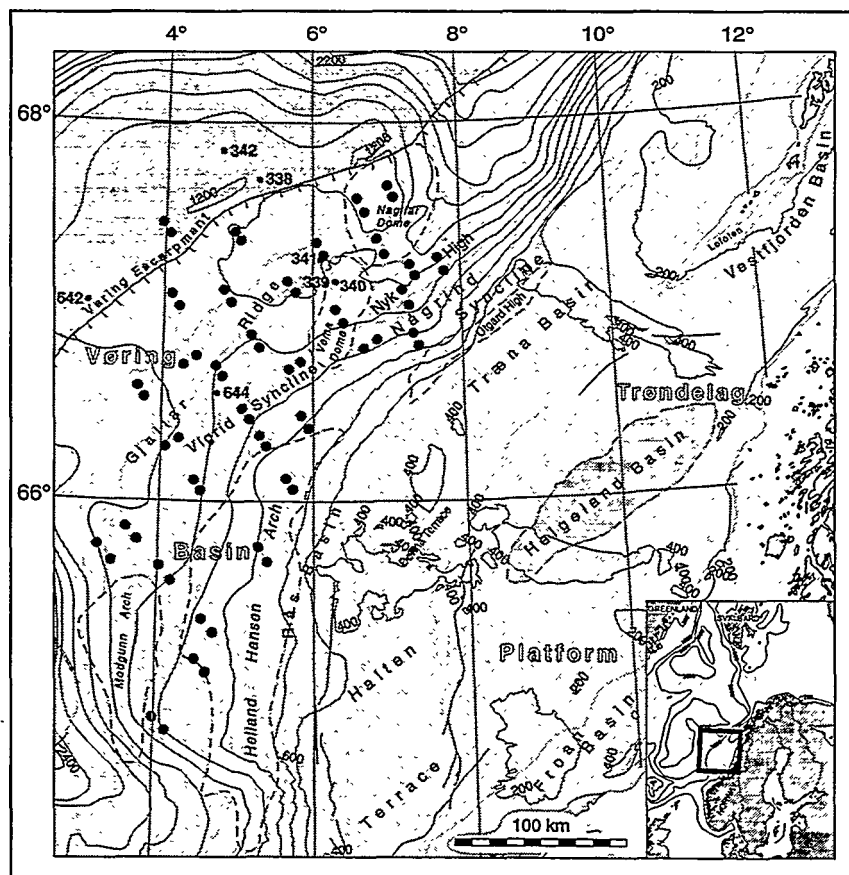


Figure 1. Location map showing the main structural elements off Mid Norway (Blystad et al., 1995). The sampling locations are marked with large dots. ODP drillings are shown with numbers and small dots (Eldholm et al., 1987, 1989).

Thermal conductivity measured with needle probe were done onboard ship just after sampling. The water content were measured in November 1994, prior to which the samples had been stored in plastic cylinders at +5 °C and a relative humidity of 80 - 100 %. Thus the sample quality might to some extent have been reduced by laboratory handling and storage over this time period. The divided bar measurements were carried out in the period of January - March 1995.

MINERALOGICAL AND TEXTURAL ANALYSIS.

Water content and porosity.

The water content (w) was determined by weighing a sample of known volume before and after drying at 105 °C for 24 hours (NS 8011). In this study water content is calculated as the ratio of the volume of water to the total volume of the sediments. Though calculation of water content is usually in weight of water to weight of dry material, we use the volume percentage of water because we consider this parameter to be more informative since it is independent of other properties of the matrix.

Porosity is often considered equal to water content estimated in volume percentage. In these samples water will also occur as water bound to minerals and organic debris. It is therefore necessary to distinguish between all water in the samples (water content) and water in the pores (porosity). Because of the very high water contents, all water was not expelled in some of the samples after 24 hours. Tests show that there were still reductions in weight when drying for more than 24 hours at 105°C. The deviation was estimated up to 3 % for the wettest samples. The original water content for these samples is therefore slightly higher than measured.

Mineralogy.

Mineralogical composition was determined by standard X-ray diffraction techniques (Brindley & Brown, 1980) at the Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology. The diffractograms were interpreted manually by calculating the areas of the characteristic peaks of the diffractograms. The peak areas were corrected by means of "weighting factors" developed by H.G Rueslåtten. The quantification is considered to be semi-quantitative with a standard deviation in the order of 5 - 10 % (Rundberg, 1991).

Grain size distribution.

The grain size fractions were determined by sieving of the material at 63 μm and Sedigraph analysis (Micromeritics 500D) of the fraction less than 63 μm . The Sedigraph is based upon Stokes' law of settling where the grain size distribution is estimated from the sedimentation of ideally shaped spheres in a liquid. To avoid flocculation a small amount of $\text{Na}_2\text{P}_2\text{O}_7$ was added to the clay suspensions.

MEASUREMENTS OF THERMAL CONDUCTIVITY.

Measurements with needle probe.

Thermal conductivity of all samples was measured onboard ship by the needle probe method developed by Von Herzen & Maxwell (1959). A probe which contains a heating wire and a thermistor, is inserted into the material. When the sample has attained thermal equilibrium, heat is introduced and the temperature is recorded as a function of time. From the temperature-time plot thermal conductivity can be determined (Von Herzen & Maxwell 1959; Jessop, 1990). In this study the value obtained is a mean value of up to four measurements, performed parallel to the assumed layering of the clays, on each sample from a given depth in the core.

Measurements with the divided bar apparatus.

To test the obtained values of thermal conductivity measured with the needle probe, 11 of the samples were measured with a divided bar apparatus. The apparatus was developed at the Department of Refrigeration Engineering, Norwegian University of Science and Technology, and is described by Brendeng & Frivik (1974). Measurements were carried out on samples prepared as cubes, $l = 3.0$ cm, with their in-situ water content preserved. The temperature difference across the samples during measurements was in the range of 1.0 - 3.5 K with a mean of 1.9 K. The apparatus was originally built for larger samples so that some minor modification of the apparatus was necessary for the present work. After modification, test measurements on samples of post glacial clay of different sizes show that the measurements were up to 3.5 % lower for samples at our size than for larger samples, $l = 40.0$ cm, $h = 10.0$ cm (H. Johansen, unpublished 1992). By the divided bar method thermal conductivities were measured both perpendicular (k_{\perp}) and parallel (k_{\parallel}) to the layering assumed on the basis of core

orientation. To test the influence of temperature on thermal conductivity the measurements were carried out at different mean temperatures in the range from 20 to 55 °C.

RESULTS OF THE LABORATORY INVESTIGATIONS.

The measured water content and the needle probe measurements of the 103 unconsolidated samples are shown in the histograms in Figures 2 and 3. Statistical data on the mineralogical composition and the grain size fractions are presented in Table 3. A thin section micrograph of a sample with textural and mineralogical characteristics is shown in Figure 4. The main minerals in the samples are quartz, albite, K-feldspar, calcite, dolomite and the clay minerals smectite, illite and kaolinite (Table 3). Small amounts of pyrite and amphibole were detected in some of the samples and traces of anhydrite and halite which are considered to be "secondary minerals" were found in all samples. Thermal conductivity values for the 11 samples measured with divided bar apparatus and the needle probe are presented in Table 4. The mineralogical and textural compositions of these samples are given in Table 5.

These laboratory investigations show the 103 samples to be sandy clay and mud according to Folk (1954) characterised by high water contents and a rather homogenous mineralogy.

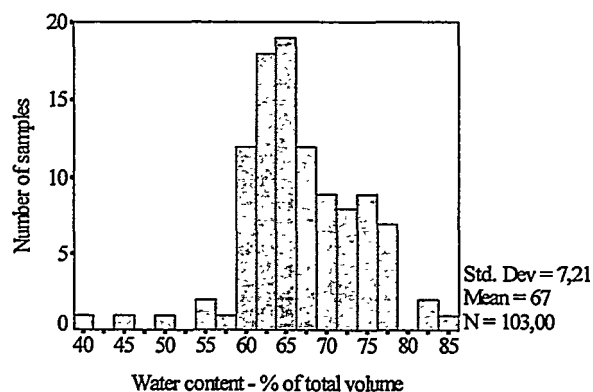


Figure 2. Distribution of water content values for the Vøring Plateau bottom sediments.

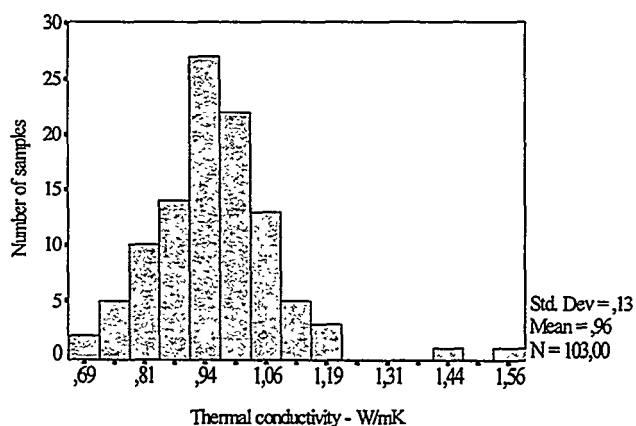


Figure 3. Distribution of thermal conductivity values for the Vøring Clays measured by needle probe.

Table 3. Statistical data of the mineralogical composition and the grain size fractions from the laboratory investigations of the 103 samples.

Mineral	Mean	Max	Minimum	Percentile 5	Percentile 95	Std Deviation
<i>Mineralogy</i>						
Quartz	28	46	16	20	37	5.4
Albite	18	32	11	13	24	3.9
K-feldspar	11	28	5	6	18	3.8
Pyrite	1	4	0	0	2	1.1
Amphibole	0	2	0	0	1	0.6
Calcite	13	30	4	6	19	4.1
Dolomite	3	13	1	1	4	1.5
Siderite	0	1	0	0	0	0.5
Kaolinite	8	13	4	6	12	1.6
Illite	13	24	5	8	17	3.2
Smectite	5	11	1	2	8	1.8
Salt	1	4	0	1	3	0.7
Anhydrite	1	2	0	1	2	0.3
<i>Grain size fractions</i>						
< 2 μm (clay)	59	72	35	46	69	7.5
2 - 63 μm (silt)	32	52	19	23	45	6.6
> 63 μm (sand)	10	46	0	1	20	7.4

Thin section micrograph of sample No. 121.

Water content:	55 %	
Mineralogy:	Quartz: 35 %	Albite: 16 %
	Microcline: 9 %	Calcite: 12 %
	Dolomite: 3 %	Kaolinite: 7 %
	Illite: 14 %	Smectite: 3 %
	Traces of pyrite and amphibol.	
Grain size fractions:	> 63 μm	11 %
	2 - 63 μm	31 %
	< 2 μm	58 %
Thermal conductivity:	Needle probe:	1.08 W/m·K
	Divided bar measured parallel to layering:	0.91 W/m·K
	Divided bar measured perpendicular to layering:	0.88 W/m·K

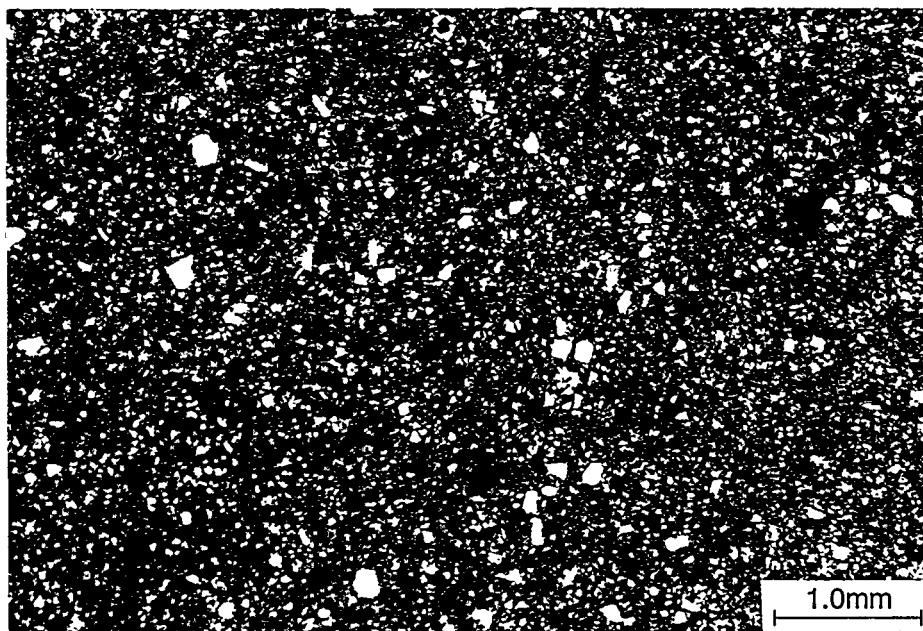


Figure 4. Thin section micrograph of sample No. 121 with the mineralogical and textural parametres.

Table 4. Comparison of thermal conductivities measured with needle probe divided bar apparatus. The divided bar measurements were carried out both parallel and perpendicular to the layering and at different measurement temperature.

Sample	Sediment depth m	Needle probe Thermal conductivity W/m·K	Temperature °C	Divided bar apparatus		Anisotropy effect $a=k_{II}/k_{\perp}$
				Thermal conductivity perpendicular k_{\perp} [W/m·K]	Thermal conductivity parallel k_{II} [W/m·K]	
No. 85			23	0.77* 0.72*		
No. 102	2.4	0.98	23 52	0.84 0.88	0.85	1.01
No. 117	0.4	1.02	21 43	0.83	0.88 0.91	1.07
No. 121	2.2	1.08	22 52	0.88	0.91 0.92	1.03
No. 123	0.5	0.97	25 49 48	0.81	0.83 0.77 0.68	1.02
No. 178	0.9	0.92	21 42	0.81 0.83	0.81	0.98
No. 180	2.1	1.07	21 46	0.80 0.82	1.09	1.37
No. 182	0.3	0.83	24 43	0.66 0.65	0.71	1.08
No. 186	2.4	0.98	22 46	0.84	0.86 0.88	1.02
No. 197	2.9	1.11	25	0.95	0.97	1.03
No. 200	1.3	0.93	24 31 37 41	0.77	0.78 0.80 0.76 0.73	1.01

* Unknown direction to the layering.

Table 5. Mineralogical and textural composition of the 11 samples measured by divided bar apparatus.

Sample	Water	Quartz	Feldspar	Calcite	Dolomite	Kaolinite	Smectite and Illite	> 63 μ m	2 - 63 μ m	< 2 μ m	Classification (Folk, 1954)
	Vol % of sample	Volum % of matrix						Weight % of matrix			
No. 85	72 ^a	22	36	13	2	8	17	13	25	62	Sandy clay
No. 102	65 ^a	21	32	12	2	9	21	11	24	65	Sandy clay
No. 117	67 ^a							10	43	47	Sandy mud
No. 121	52 ^a	35	25	12	3	7	17	11	31	58	Sandy mud
No. 123	77 ^a	28	36	12	2	6	14	20	40	40	Sandy mud
No. 178	73	32	27	10	2	8	18	10	29	61	Sandy mud
No. 180	66	35	29	10	2	8	14	18	26	56	Sandy clay
No. 182	79	26	26	14	3	8	18	0	42	58	Mud
No. 186	69	21	27	14	2	10	24	5	29	66	Muddy clay
No. 197	61	37	26	12	1	7	15	17	28	55	Sand mud
No 200	72	37	22	12	5	8	14	4	43	53	Mud

^a The samples were sealed and stored at room temperature for up to two weeks before the water content were measured.

The anisotropy of thermal conductivity.

A generally small but noticeable anisotropy in the measured thermal conductivity ($a = k_{II} / k_{\perp}$) was obtained for most of the samples measured by the divided bar apparatus (Figure 5). The highest anisotropy ($a = 1.37$) was obtained for sample No. 180. There is nothing from the sediment depth (Table 4) and mineralogical and textural data (Table 5, Figure 6) which can explain the high anisotropy effect of this sample, neither a higher content of the platy clay minerals nor deeper burial. Early during the field measurements, a limited number of shipboard needle probe measurements were performed on samples where the probe was inserted both parallel and perpendicular to the core axes. Within the experimental error of the measurements, 3 - 4 % (e.g., Von Herzen and Maxwell, 1959), no evidence for anisotropy was observed. Excluding sample No. 180, the remaining samples (Table 4) show an average increase in thermal conductivity (perpendicular to parallel) of 3.2 %, with six of these nine samples at 2.5% or less. Within these limits the anisotropy results for the needle probe appear consistent with those of the divided bar apparatus.

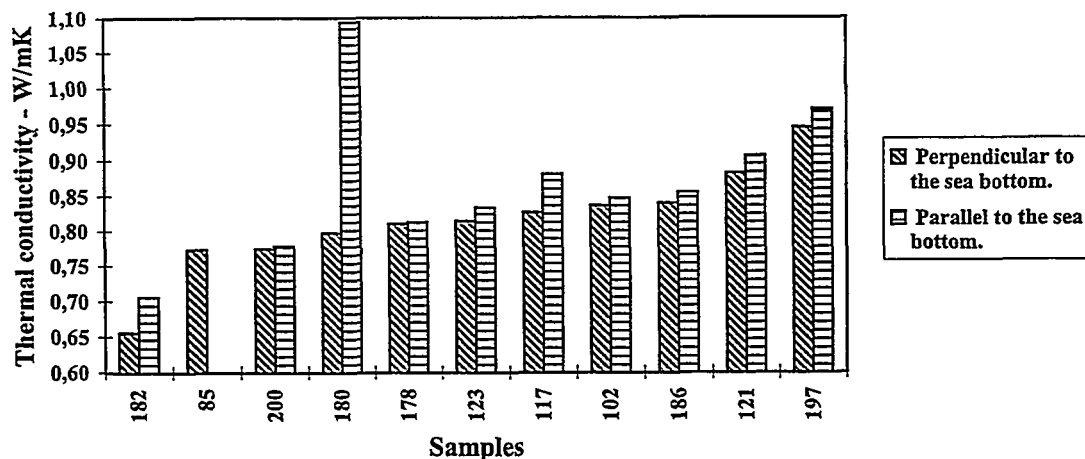


Figure 5. Thermal conductivity measured with divided bar apparatus parallel and perpendicular to the assumed layering. Values measured parallel to the layering are higher than the perpendicular values. Sample No. 180 represents the most extreme case.

Thin section micrograph of sample No. 180.

Water content:	66 %		
Mineralogy:	Quartz: 35 %	Albite: 18 %	
	Microcline: 11 %	Calcite: 10 %	
	Dolomite: 2 %	Kaolinite: 8 %	
	Illite: 10 %	Smectite: 4 %	
	Traces of pyrite and amphibol.		
Grain size fractions:	> 63 μm : 18 %		
	2 - 63 μm : 26 %		
	< 2 μm : 56 %		
Thermal conductivity:	Needle probe:	1.07 W/m-K	
	Divided bar measured parallel to layering:	1.09 W/m-K	
	Divided bar measured perpendicular to layering:	0.80 W/m-K	

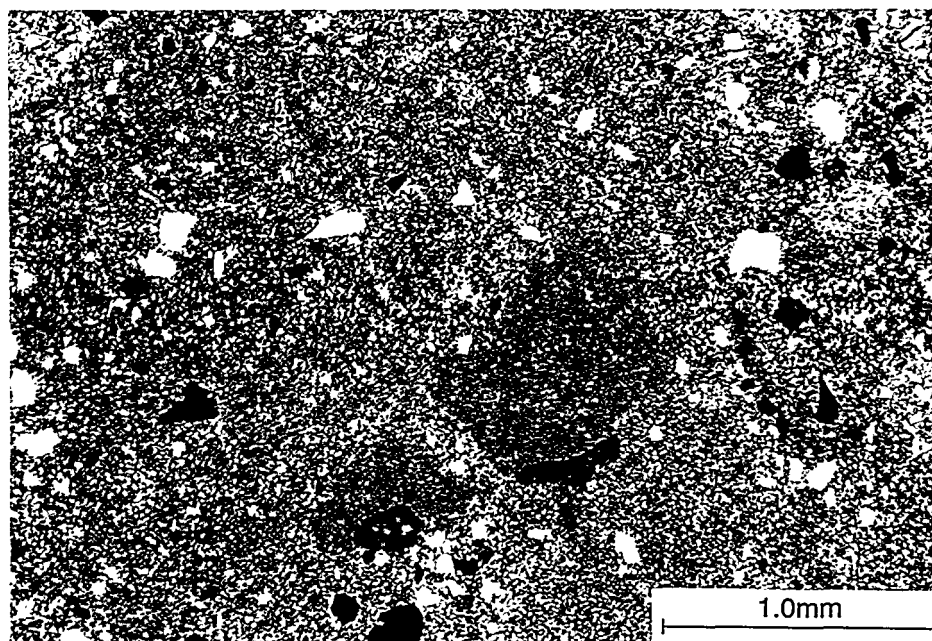


Figure 6. Thin section micrograph of sample No. 180. An anisotropy of thermal conductivity of 1.37 was measured for this sample.

The temperature effect on thermal conductivity.

The temperature effect on thermal conductivity is shown in Figure 7. In general the thermal conductivity increases slightly with increasing temperature. The decrease in thermal conductivity for samples No. 123 and No. 200 may be due to drying and crack formation in the samples and those data are considered erroneous. Unpublished data from Butler (Ratcliffe, 1960) show a 6 % increase in the thermal conductivity of ocean bottom sediments from 4 °C to 25 °C which is attributed largely to the increase in thermal conductivity of water over that interval. The thermal conductivity temperature coefficient for water over the temperature range of the divided bar measurements in the range from 20 °C to 50 °C is about 0.2 % per °C (e.g., Clark, 1966). The corresponding coefficient for the samples based on the data in Table 4 is 0.10 % per °C.

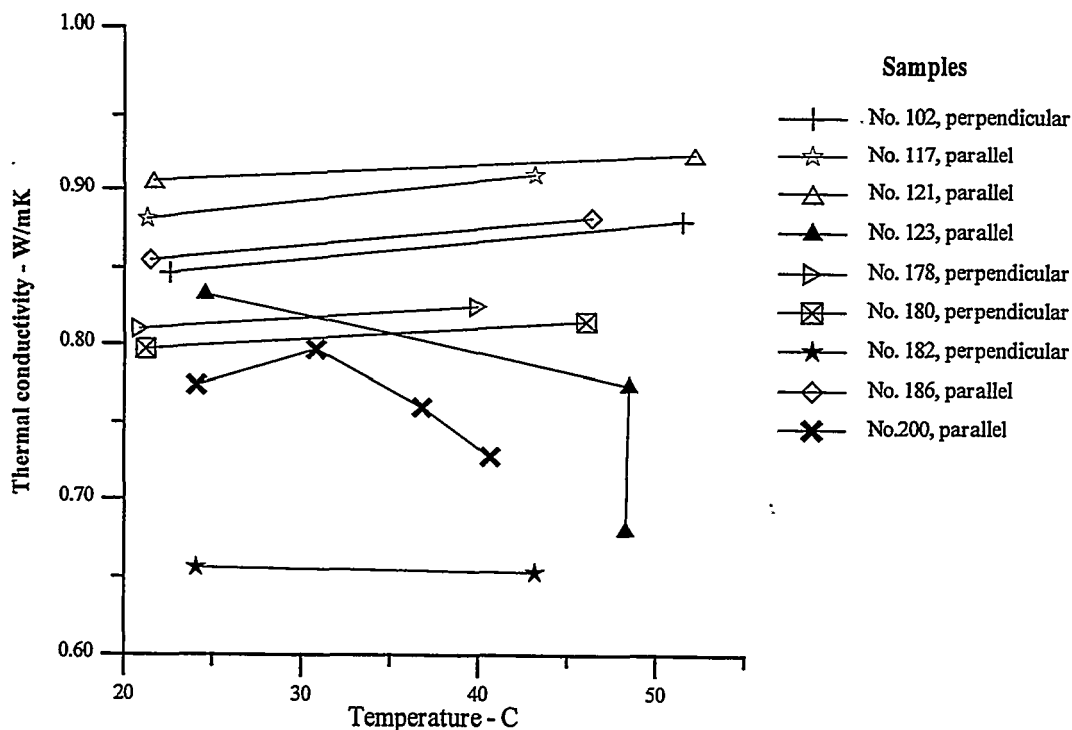


Figure 7. Variation in thermal conductivity with increasing measurement temperature.

Comparative measurements.

Thermal conductivities measured by needle probe and divided bar apparatus are shown in Figure 8. The needle probe represents a combined value of parallel and perpendicular thermal conductivity. In order to compare the two methods, values of the parallel and perpendicular divided bar measurements are used to calculate k_m from Equation 5, which is derived from the basic equation for an ellipse (e.g. Penner, 1963; Demongodin et al., 1993). Values of k_m (blue circles, Figure 8) should approximate needle probe measurements geometry.

$$k_m = \sqrt{k_{\perp} \cdot k_{\parallel}} \quad (5)$$

where k_m - thermal conductivity estimated from the parallel and perpendicular measured divided bar values.

There is a near constant difference between the measured values of thermal conductivity returned by the two methods. In Figure 8 it can be seen that the needle probe method measures consistently higher values of thermal conductivity (red squares, Figure 8) for all samples, than those obtained from the divided bar method, represented by k_m (blue circles, Figure 8).

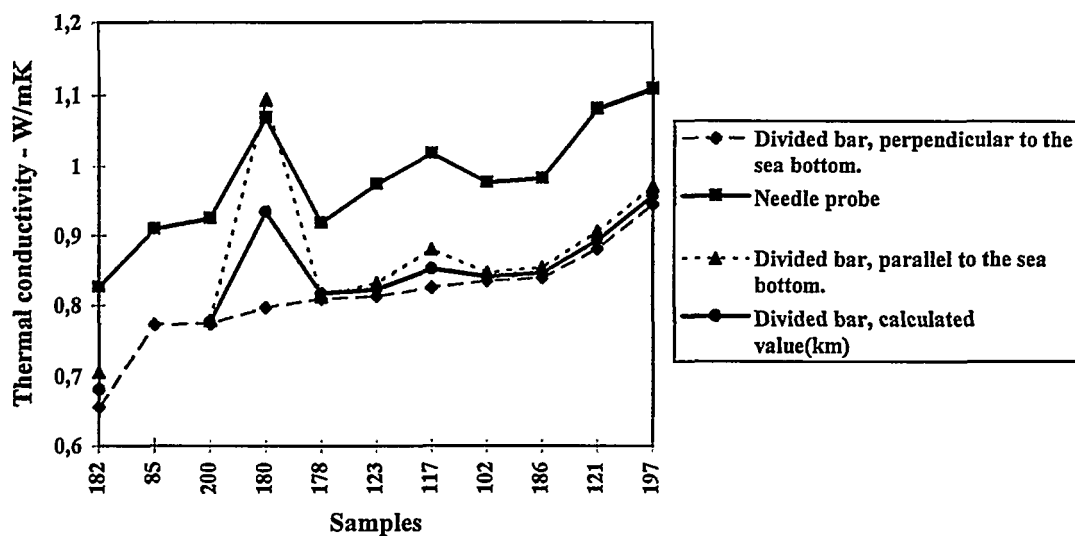


Figure 8. Comparison of thermal conductivities measured with needle probe and divided bar apparatus. The needle probe measurements are higher than those measured with the divided bar apparatus.

Even when a correction for the small sample size in the divided bar measurements is made, the discrepancy between the two methods of measurements is reduced only by 3.5 % and thus remains significant. Some difference between the measurements might be expected due to inhomogeneities in the tested samples since the divided bar measurements were carried out on a part of the needle probe samples. However, since the difference observed in Figure 8 can be considered as constant (where 7 of the 10 pairs of measurements differ in the range of 0.13 - 0.15 W/m-K) random inhomogeneity is not a likely explanation. The observed difference might, however, be due to:

- calibration error
- errors caused by drying of the samples during storage
- errors caused by the preparation of the samples
- errors caused by environmental conditions during measurements.

Calibration error.

A calibration error is a measurement error related to the instrument and the measurement methodology expressed as lack of correspondence between the two different methods. This will be a systematic error. The difference in our results obtained by the two methods is similar to that reported previously by Slusarchuk & Foulger (1973), Farouki (1981) and Somerton (1992). Their measurements with the needle probe techniques were in the range of 15 - 20 % higher than those with the divided bar apparatus. Also previously unpublished measurements carried out at Department of Refrigeration Engineering, Norwegian University of Science and Technology confirm a methodical discrepancy (H. Johansen, pers. comm. 1996), where a needle probe was inserted in the divided bar samples during the measurements. The needle probe measured about 20 % higher thermal conductivity than the divided bar. This result disagrees with the measurements on clayey unconsolidated sediments by Von Herzen & Maxwell (1959) and consolidated samples by Brigaud & Vasseur (1989) who did not detect any discrepancy between the two methods. Slusarchuk & Foulger (1973) and Farouki (1981) postulated that calibration error may explain their measured discrepancy between the two methods. Slusarchuk & Foulger (1973) and Farouki (1981) considered the values obtained by the divided bar apparatus as the most correct thermal conductivity value.

Errors caused by drying of the samples during storage.

As the needle probe measurements were carried out onboard ship just after sampling, while the divided bar measurements were performed up to 7 months later drying of the samples during storage might be a reason for the lower values measured with the divided bar apparatus (e.g., Von Herzen & Maxwell, 1959). The considerable lowering of thermal conductivity with increasing temperature for samples No. 123 and No. 200 (Figure 7) is probably due to drying of the samples. If drying was the main reason for the discrepancy, a random and not as observed a rather constant discrepancy between the methods, would be expected. The 11 samples have a high water content in the range of 53 - 79 % (Table 4), and they have been subjected to the same physical conditions in the time between the needle probe and the divided bar measurements. The divided bar measurement of sample No. 197 at 25 °C and sample 200 at 41 °C were reproduced after respectively 4 and 8 days. The samples were stored in the divided bar apparatus. Exactly the same thermal conductivity values were obtained for both of the samples. For sample No. 123 a decrease in the measured thermal conductivity of 7 % and 18% was observed after lying respectively one and two days in the divided bar apparatus. A small temperature effect is included in this reduction. From these results and also from experience gained from measurements carried out on claystones from England (Midttømme et al., 1997a) drying of the samples seems to cause a pronounced lowering of the thermal conductivity. We would from our experience have expected this drying effect to be random. On the other hand, because of the character of these samples we will not exclude that there might be a systematic effect of drying on the divided bar results.

Errors caused by preparation of the samples.

The divided bar apparatus requires a more exact and comprehensive preparation of the samples (Von Herzen & Maxwell, 1959; Farouki, 1981). This may be a drawback especially for soft sediments. Compaction, drying and some disturbance of the sample may occur during the preparation process and influence the measured thermal conductivity. Compaction and disturbance of the samples during preparation are assumed to increase the thermal conductivity and these effects are also expected to cause a more random discrepancy in the measurements, and cannot therefore explain the observed discrepancy in the measured thermal conductivity. (e.g., Von Herzen & Maxwell, 1959). Drying of the samples will occur during preparing, and this might, as discussed above, have lowered the thermal conductivity measured with the divided bar apparatus.

Errors caused by the environmental conditions.

Temperature is found to influence thermal conductivity of these samples (Figure 7). The divided bar measurements were carried out at temperatures from 20 - 25 °C while the temperature range of the needle probe measurements was 10 - 20 °C. Based on the previous discussion correction for this effect would serve to increase the difference between the measurements by about 3 % at most. The effect of pressure is not significant as all measurements were carried out at about normal atmospheric pressure.

Total effect of errors.

The effects of sample size and the differences in ambient temperatures during measurements are seen to essentially cancel each other.

Von Herzen and Maxwell (1959) emphasize the need for measuring thermal conductivity shortly after a core is retrieved and point to changes in thermal conductivity of up to 20%, possible in relatively short times. They did not discuss the possibility of an increase or a decrease in the thermal conductivity due to this time lag. In view of the unavoidably long time between needle probe and divided bar measurements in the present study (up to seven months), ample time was available for such effects to come to play. However, the fact that we observe a constant discrepancy which is similar to prior reports of a calibration error between the two methods of thermal conductivity measurement is disquieting. Resolution of this discrepancy is beyond the scope of our measurements largely due to the previously discussed time factor. The implications of the discrepancy; however, as well as the numbers of conflicting reports are sufficient to warrant additional work in this area.

However, for the purposes of the present work on modeling sample to sample differences in thermal conductivity, Figure 8 shows a high degree of sample to sample correlation between the needle probe and the divided bar measurements. This lends confidence to our thermal conductivities measured by the needle probe as the basis for the modeling work which follows. There might also be a change in thermal conductivity due to changes in the samples compressibility because of the removal from its initial stress-state. This effect is not considered in this study.

Modeling thermal conductivity.

Thermal conductivity was estimated by the geometric mean model (Equation 1) using the measured water content values and a constant water conductivity, k_w , of 0.60 W/m·K. The matrix conductivity, k_s was calculated: 1) from the mineralogy (Equation 4) by using the Horai (1971) values of mineral conductivities (Table 1) and 2) by Johansen's (1975) method (Equation 6), which is based on the quartz content.

$$k_s = k_{qz}^{V_{qz}} \cdot k_o^{1-V_{qz}} \quad (6)$$

where

k_{qz}	-	quartz conductivity, 7.70 W/m·K,
k_o	-	thermal conductivity of the other minerals, 2.00 W/m·K,
V_{qz}	-	content of quartz (0.00 - 1.00).

The values calculated were plotted versus measured thermal conductivity values carried out by the needle probe method (Figure 9). Both models calculated higher values than the measured. Of the two models Johansen's model predicts thermal conductivities better than the model based on the total mineralogy. The mean deviation between estimated and measured values are respectively 0.06 W/m·K (6 %) and 0.11 W/m·K (12 %). From these results, except for a possible effect of quartz, there seems to be low correlation between the mineralogy and the measured thermal conductivity for these unconsolidated, water rich sediments.

In an attempt to develop a better model for the studied sediments, and to test the influence of the mineral properties, different models of thermal conductivity are proposed and tested. Thermal conductivities measured by needle probe are taken to give the correct results. The models are predicted by the geometric mean equation (Equation 1) where thermal conductivity of the water is taken as constant, $k_w = 0.60$ W/m·K for all models. The models differ as to how the matrix thermal conductivity (k_s) is estimated. Four methods to model matrix conductivity have been tested:

1. k_s as a constant
2. k_s estimated from the mineralogy
3. k_s estimated from the grain size fractions
4. k_s estimated from the mineralogy and grain size fractions.

In methods 2, 3 and 4 the matrix conductivity is estimated from the geometric mean equation (Equation 2). The models were tested by non-linear regression analysis of the geometric mean model, where the laboratory data of water content, mineralogy and grain size distribution are used as the

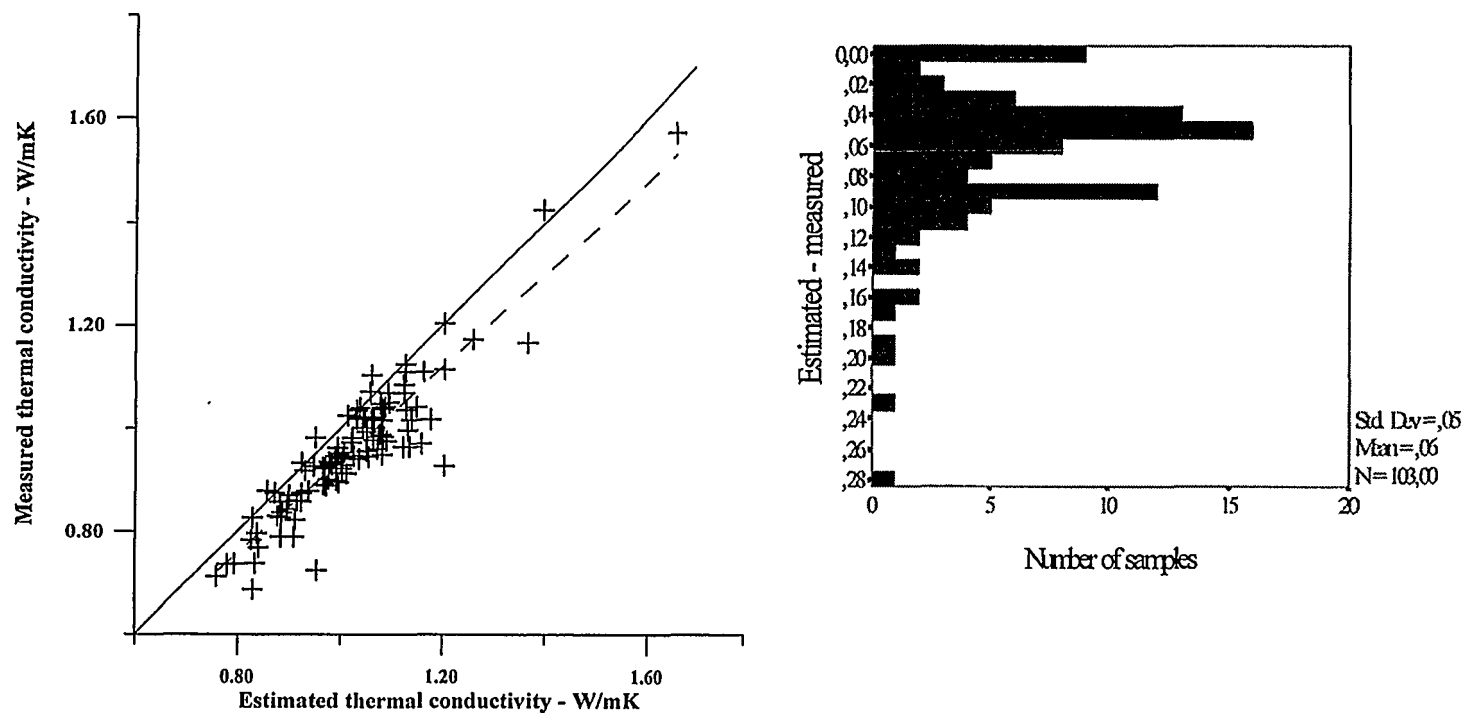


Figure 9a Thermal conductivities estimated with Johansen's (1975) method versus values measured with the needle probe. The solid line is the unity line (1:1). The dotted line is the regression line. The deviation between the estimated and measured values are shown in the histogram.

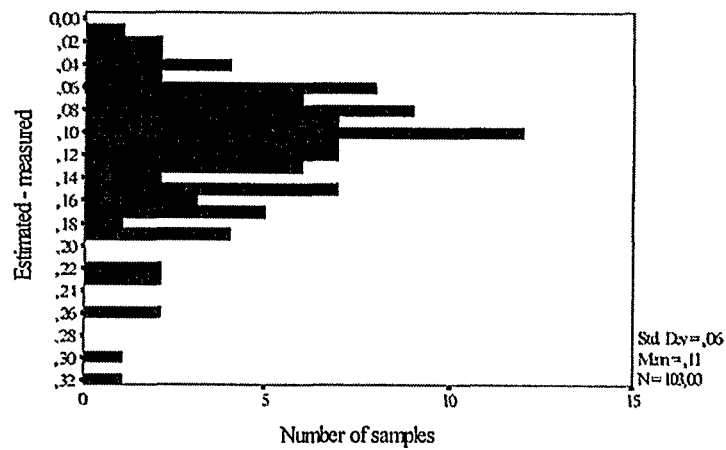
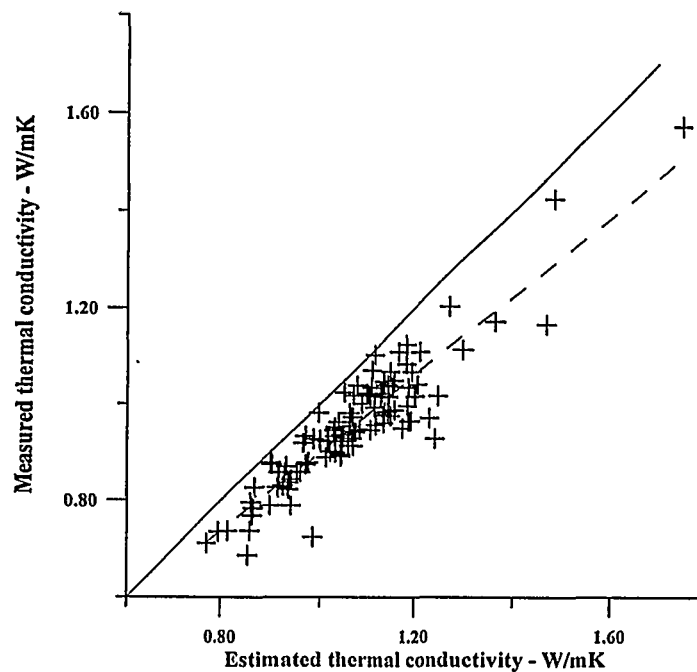


Figure 9b Thermal conductivities estimated with the geometric mean model based on the mineralogy versus values measured with the needle probe. The solid line is the unity line (1:1). The dotted line is the regression line. The deviation between the estimated and measured values are shown in the histogram.

variables. Based on the thermal conductivities measured with the needle probe, the thermal conductivities of the minerals and grain size fractions were determined by regression analysis. The analyses were run by the statistical program SPSS 6.1 for Windows. A total of 24 mineralogical models (Models 2.1 - 2.24) and 3 grain size models (Models 3.1 - 3.3) were tested. Results of the statistical analysis are presented in Table 6. The coefficient of determination, R^2 is the adjusted coefficient to which corrects for the number of independent variables.

Model 1. k_s as a constant.

Model 1 is the simplest model where both thermal conductivities of water, k_w and matrix, k_s are considered to be constants. The thermal conductivity is then expressed as a function of the water content only. The best fit result from the regression analysis (Table 6) was when k_s was 2.45 W/m·K. A coefficient of determination, R^2 of 0.813, was then obtained. Model 1 is shown in the scatterplot of thermal conductivity versus water content (Figure 10). By this simple model where all qualitative information of the matrix is ignored, thermal conductivity is estimated within a standard error estimates of 20 %. This result emphasizes the major influence of water content on the thermal conductivity of these sediments, and clearly demonstrates the decrease in thermal conductivity as the water content increases. Figure 10 shows best agreement between Model 1 and the measured thermal conductivities when the water content is in the range of 60 - 75 %. The measured values for the samples with highest water content are lower than the values predicted with this model. The water content of these samples are, as mentioned previously probably too low (< 3 %). A small increase in the water content for these samples would improve the coefficient of determination and the quality of the model.

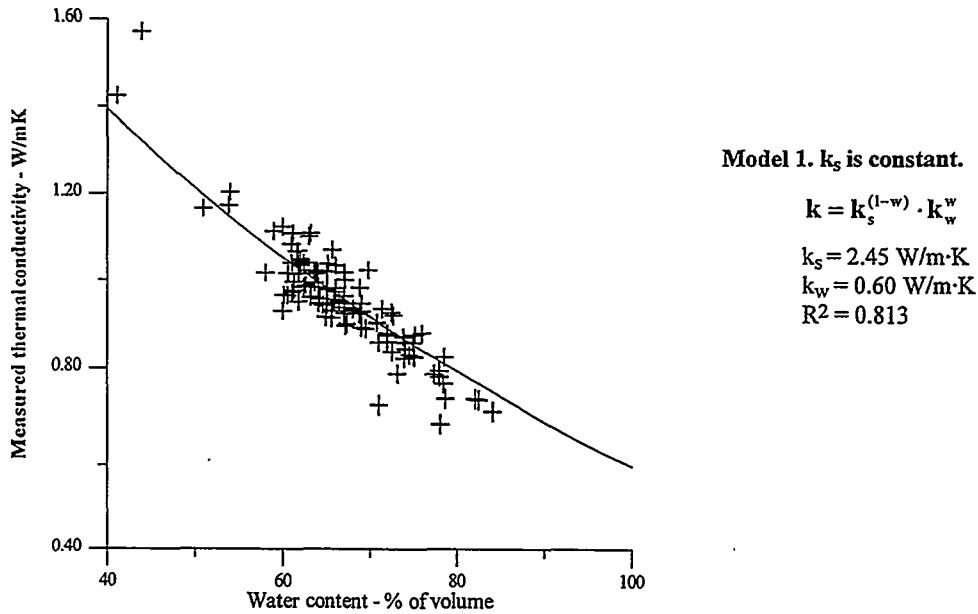


Figure 10. Scatterplot of water content versus measured thermal conductivity. The line represents the simplest model (Model 1), where k_s is constant.

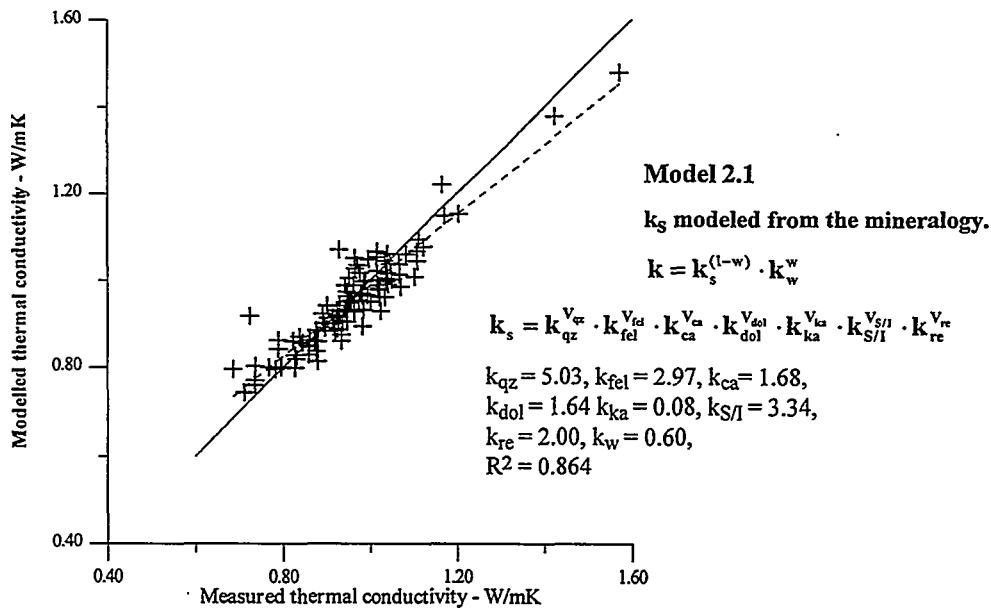


Figure 11. Values of thermal conductivities obtained by the best mineralogy model (Model 2.1) versus measured thermal conductivities. Unity relationship (1:1) is shown with solid line. Linear regression is shown with dotted line.

Model 2. k_s dependent on the mineralogy.

Different mineral dependent models were tested with use of different contents of minerals (Table 6). The 7 main minerals in the samples; quartz, feldspar, calcite, dolomite, kaolinite, illite and smectite are used in the modeling. The contents of illite, smectite and mixed layer illite/smectite are combined and named smectite/illite. The best fit model (Model 2.1) was obtained when the calculation of the matrix thermal conductivity (k_s) was based on all 6 mineral fraction (Figure 11).

$$k_s = k_{qz}^{V_{qz}} \cdot k_{fsp}^{V_{fsp}} \cdot k_{ca}^{V_{ca}} \cdot k_{dol}^{V_{dol}} \cdot k_{ka}^{V_{ka}} \cdot k_{S/I}^{V_{S/I}} \cdot k_{re}^{V_{re}} \quad (7)$$

where

V_i	-	volume fraction of mineral i,
k_{qz}	-	thermal conductivity of quartz = 5.03 W/m·K,
k_{fsp}	-	thermal conductivity of feldspar = 2.97 W/m·K,
k_{ca}	-	thermal conductivity of calcite = 1.68 W/m·K,
k_{dol}	-	thermal conductivity of dolomite = 1.64 W/m·K,
k_{ka}	-	thermal conductivity of kaolinite = 0.08 W/m·K,
$k_{S/I}$	-	thermal conductivity of smectite and illite = 3.34 W/m·K,
k_{re}	-	thermal conductivity of remaining minerals = 2.00 W/m·K

The coefficient of determination, R^2 is 0.864 for this model, which is an improvement on the simplest model (Model 1) by 5.1 %. Some trends are observed from the 24 different mineralogical models (Models 2.1 - 2.24 in Table 6) and the correlation matrix (Table 7). The coefficients of determination show that of the 6 mineral fractions, quartz has the greatest, and feldspar and dolomite the least influence on thermal conductivity. Values of mineral conductivities obtained from the statistical analysis are given in Table 6. In agreement with the literature values (Table 1) quartz is found to have the highest mineral conductivity, but the values of mineral conductivity in the mineralogical models 2.1 - 2.24 do in general not correspond with those reported in the literature. A particularly high deviation is detected for the mineral conductivities of kaolinite and dolomite. A mineral conductivity of 0.08 W/m·K for kaolinite which is only 7 % of thermal conductivity of water appears unrealistic.

Model 3. k_s dependent on grain size distribution.

Three grain size models were tested. The thermal conductivities of the grain size fractions were found from the best fit results from the regression analyses (Table 6). A coefficient of determination, R^2 of 0.878 was obtained by two of the models, respectively when all three fractions (Equation 8) and when only the coarsest fraction is used (Figure 12) (Equation 9).

$$k_s = k_{>63}^{V_{>63}} \cdot k_{2-63}^{V_{2-63}} \cdot k_{<2}^{V_{<2}} \quad (8)$$

where V_i - volume fraction of the grain size fraction i ,
 $k_{>63}$ - thermal conductivity of the grain fraction $>63 \mu\text{m} = 5.24 \text{ W/m}\cdot\text{K}$,
 k_{2-63} - thermal conductivity of the grain fraction $2 - 63 \mu\text{m} = 2.00 \text{ W/m}\cdot\text{K}$,
 $k_{<2}$ - thermal conductivity of the grain fraction $<2 \mu\text{m} = 2.26 \text{ W/m}\cdot\text{K}$.

$$k_s = k_{>63}^{V_{>63}} \cdot k_{<63}^{V_{<63}} \quad (9)$$

where $k_{>63}$ - thermal conductivity of the grain fraction $>63 \mu\text{m} = 5.19 \text{ W/m}\cdot\text{K}$,
 $k_{<63}$ - thermal conductivity of the grain fraction $<63 \mu\text{m} = 2.17 \text{ W/m}\cdot\text{K}$.

The high influence of the coarsest grain size fraction ($> 63 \mu\text{m}$) on the thermal conductivity is confirmed by the correlation coefficient matrix (Table 7). Next to water content, this fraction has the highest correlation with the measured thermal conductivity ($r = 0.81$). Using only the finest grain size fraction (Model 3.3) a coefficient of determination, $R^2 = 0.860$ is obtained, which is better than the mineralogical models 2.2 - 2.24, but slightly worse than Model 2.1.

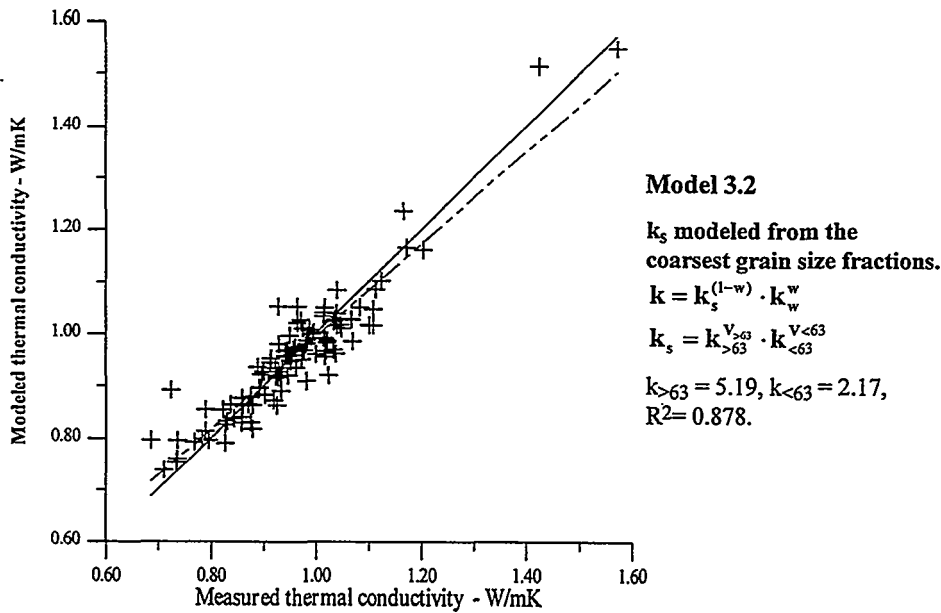


Figure 12. Thermal conductivities modeled from the grain size fraction $> 63 \mu\text{m}$ (Model 3.2) versus measured thermal conductivities. Unity relationship (1:1) is shown with solid line. Linear regression is shown with dotted line.

Table 7. Correlation matrix of thermal conductivity, water content, grain size and mineralogical characteristics.

	Thermal cond.	Water content	> 63 μ m	2-63 μ m	< 2 μ m	Quartz	Feldspar	Calcite	Dolomite	Kaolinite	Illite/smectite
Thermal conductivity	1	-090	081	-053	-039	038	010	-021	-001	-035	-019
Water content	-090	1	-072	060	022	-031	-008	017	002	025	013
> 63 μ m	081	-072	1	-049	-062	044	027	-031	-007	-049	-028
2-63 μ m	-053	060	-049	1	-038	-016	-004	025	-004	005	-009
< 2 μ m	-039	022	-062	-038	1	-032	-025	010	012	049	038
Quartz	038	-031	044	-016	-032	1	-017	-040	002	-031	-054
Feldspar	010	-008	027	-004	-025	-017	1	-041	-019	-040	-030
Calcite	-021	017	-031	025	010	-040	-041	1	-007	005	-029
Dolomite	-001	002	-007	-004	012	002	-019	-007	1	001	-012
Kaolinite	-035	025	-049	005	049	-031	-040	005	001	1	044
Illite/smectite	-019	013	-028	-009	038	-054	-030	-029	-012	044	1

Model 4. k_s dependent on the mineralogy and grain size distribution.

The best model is obtained using both the mineralogical and grain size fractions. The matrix conductivity is estimated from the following equation:

$$k_s = x(k_{qz}^{V_{qz}} \cdot k_{fsp}^{V_{fsp}} \cdot k_{ca}^{V_{ca}} \cdot k_{ka}^{V_{ka}} \cdot k_{s/I}^{V_{s/I}} \cdot k_{re}^{V_{re}}) + (1-x)(k_{>63}^{V_{>63}} \cdot k_{2-63}^{V_{2-63}} \cdot k_{<2}^{V_{<2}}) \quad (10)$$

where	x	-	ratio estimated from the mineralogical parameters = 0.24
	V_i	-	volume fraction of mineral and grain size fraction i ,
	k_{qz}	-	thermal conductivity of quartz = 6.82 W/m·K,
	k_{fsp}	-	thermal conductivity of feldspar = 3.49 W/m·K,
	k_{ca}	-	thermal conductivity of calcite = 3.62 W/m·K,
	k_{ka}	-	thermal conductivity of kaolinite = 0.06 W/m·K,
	$k_{s/I}$	-	thermal conductivity of smectite and illite = 1.61 W/m·K,
	k_{re}	-	thermal conductivity of remaining minerals = 3.43 W/m·K,
	$k_{>63}$	-	thermal conductivity of grain size fraction >63 μ m = 5.46 W/m·K,
	k_{2-63}	-	thermal conductivity of grain size fraction 2-63 μ m = 1.80 W/m·K,
	$k_{<2}$	-	thermal conductivity of grain size fraction <2 μ m = 2.22 W/m·K.

With a coefficient of determination of 0.883 this model improves the calculation of thermal conductivity by 7.0 % compared to the simplest model (Model 1). A value of x of 0.24 will mean that the grain size fractions have three times greater influence on thermal conductivity in this model than the mineralogy. An improvement of only 7 % of the results by the rather complex Model 4 compared to the simple Model 1 is lower than expected. This is in view of the fact that heat is mainly transferred through the solid part of the samples. Though this study is based on samples with low matrix volume (15-60 %) (Figure 2) and relatively small variations in mineralogy and grain size distribution (Table 3), the matrix properties were expected to have greater influence on thermal conductivity.

Related to the conductivities of the grain size fractions (Table 6) the coarsest fraction ($>63 \mu\text{m}$) has considerably higher conductivity than the two other fractions. Noticeable is that the finest fraction ($<2 \mu\text{m}$) is found to have higher conductivity than the medium fraction ($2-63 \mu\text{m}$). Compared with the literature values of mineral conductivity (Table 1) the values obtained by this model (Model 4), with one exception, are more reasonable than those obtained from the mineralogical models (Models 2.1 - 2.24). In this model the mineralogical conductivities of quartz, calcite and illite/smectite are close to the values previously reported in the literature. The conductivity of kaolinite still appears unrealistically low.

Model 4. k_s modeled from mineralogy and grain size fractions.

$$k = k_s^{(1-w)} \cdot k_w^w$$

$$k_s = x(k_{qz}^{V_{qz}} \cdot k_{fsp}^{V_{fsp}} \cdot k_{ca}^{V_{ca}} \cdot k_{ka}^{V_{ka}} \cdot k_{S/I}^{V_{S/I}} \cdot k_{re}^{V_{re}}) + (1-x)(k_{>63}^{V_{>63}} \cdot k_{2-63}^{V_{2-63}} \cdot k_{<2}^{V_{<2}})$$

$$x = 0.24, k_{qz} = 6.82, k_{fsp} = 3.49, k_{ca} = 3.62, k_{ka} = 0.06, k_{S/I} = 1.61, k_{re} = 3.43, \\ k_{>63} = 5.46, k_{2-63} = 1.80, k_{<2} = 2.22 \\ R^2 = 0.883.$$

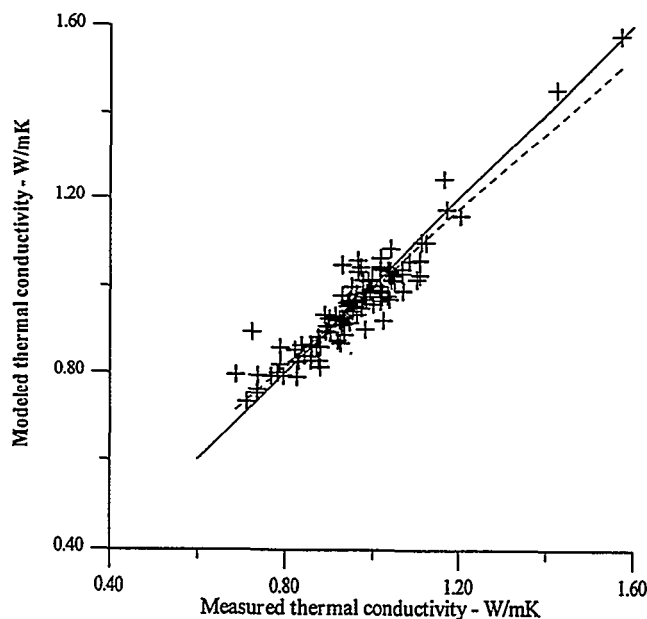


Figure 13. Thermal conductivities for the "best fit" model (Model 4) versus measured thermal conductivities. Unity relationship (1:1) is shown with solid line. Linear regression is shown with dotted line.

Improvement of the thermal conductivity of kaolinite.

In Models 4.1.1- 4.1.7 (Table 8, Figure 14) different values for the mineral conductivity of kaolinite are tested. The conductivities of the other minerals and the grain size fractions are the same as in Model 4 (Table 6). As seen in Figure 14 an increase in the assumed conductivity of kaolinite will highly degrade the quality of the model. When using the standard conductivity of kaolinite, $k_{ka} = 2.8$ W/m·K (Table 1), an adjusted coefficient of determination, $R^2 = 0.822$ is obtained which is the lowest of all mineralogical and grain size dependent models, except for the feldspar dependent model (Model 2.24).

Table 8. Improvement of Model 4 with regard to the thermal conductivity of kaolinite. The other thermal conductivities of the mineral and grain size fraction remain constant equal those obtained in Model 4.

Model	Thermal conductivity of kaolinite W/m·K	Coefficient of determination R^2
4	$k_{ka} = 0.06$	$R^2 = 0.883$
4.1.1	$k_{ka} = 0.50$	$R^2 = 0.867$
4.1.2	$k_{ka} = 1.00$	$R^2 = 0.853$
4.1.3	$k_{ka} = 1.50$	$R^2 = 0.842$
4.1.4	$k_{ka} = 2.00$	$R^2 = 0.834$
4.1.5	$k_{ka} = 2.50$	$R^2 = 0.826$
4.1.6	$k_{ka} = 2.80$	$R^2 = 0.822$
4.1.7	$k_{ka} = 3.00$	$R^2 = 0.820$

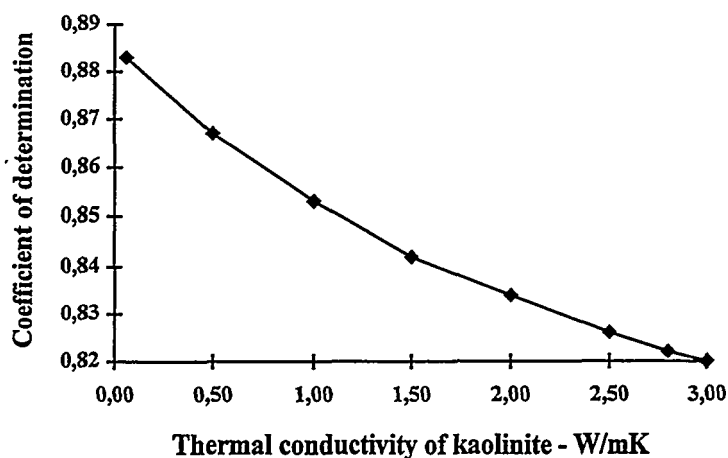


Figure 14. Thermal conductivity of kaolinite plotted versus the coefficient of determination obtained by the Models 4, 4.1.1 - 4.1.7. The 8 models are plotted from left.

Since thermal conductivities of grain size fractions have not been previously published, it is difficult to confirm the values obtained in Model 4. In models 4.2.1-4.2.7 (Table 9, Figure 15) the conductivity of kaolinite has also been adjusted. The conductivities of the grain size fractions are allowed to vary, and the best fit models are determined by non-linear regression analysis. The other mineral conductivities remain constant. For these models only a slight worsening in the coefficient of determination is obtained when increasing the conductivity of kaolinite. The increase in kaolinite conductivity is accompanied by a decrease in the conductivity of $< 2 \mu\text{m}$ and $2-63 \mu\text{m}$ fractions and an increase in the $>63 \mu\text{m}$ fraction (Figure 15). We have no explanation of these results.

Table 9. Improvement of Model 4 with regard to the thermal conductivity of kaolinite. The other mineral conductivities remain constant equal those in Model 4. The grain size conductivities are allowed to vary. The best fit models are determined by non-linear regression analysis.

Model	Thermal conductivity of kaolinite W/m·K	Thermal conductivity of $>63\mu\text{m}$ fraction W/m·K	Thermal conductivity of $2-63\mu\text{m}$ fraction W/m·K	Thermal conductivity of $< 2\mu\text{m}$ fraction W/m·K	Coefficient of determination R^2
4	$k_{ka} = 0.06$	$k_{>63} = 5.46$	$k_{2-63} = 1.80$	$k_{<2} = 2.22$	$R^2 = 0.883$
4.2.1	$k_{ka} = 0.50$	$k_{>63} = 5.57$	$k_{2-63} = 1.65$	$k_{<2} = 2.05$	$R^2 = 0.883$
4.2.2	$k_{ka} = 1.00$	$k_{>63} = 5.64$	$k_{2-63} = 1.60$	$k_{<2} = 1.99$	$R^2 = 0.883$
4.2.3	$k_{ka} = 1.50$	$k_{>63} = 5.69$	$k_{2-63} = 1.57$	$k_{<2} = 1.95$	$R^2 = 0.883$
4.2.4	$k_{ka} = 2.00$	$k_{>63} = 5.74$	$k_{2-63} = 1.54$	$k_{<2} = 1.92$	$R^2 = 0.883$
4.2.5	$k_{ka} = 2.50$	$k_{>63} = 5.77$	$k_{2-63} = 1.53$	$k_{<2} = 1.90$	$R^2 = 0.882$
4.2.6	$k_{ka} = 2.80$	$k_{>63} = 5.79$	$k_{2-63} = 1.52$	$k_{<2} = 1.89$	$R^2 = 0.882$
4.2.7	$k_{ka} = 3.00$	$k_{>63} = 5.80$	$k_{2-63} = 1.51$	$k_{<2} = 1.88$	$R^2 = 0.882$

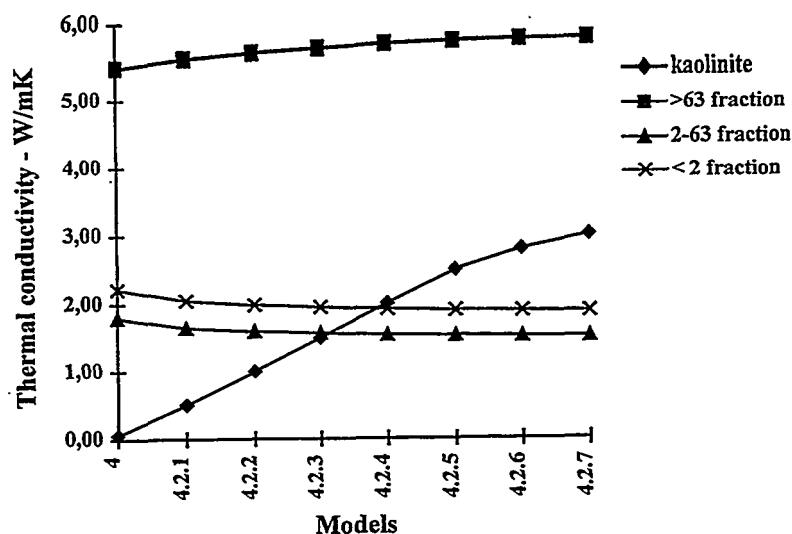


Figure 15. Variation in the conductivity of kaolinite, $>63\mu\text{m}$ fraction, $2-63\mu\text{m}$ fraction and $<2\mu\text{m}$ fraction. (Models 4.2.1 - 4.2.7).

For these unconsolidated sediments the most reasonable model proposed, related to previously published mineral conductivities (e.g. Horai, 1971; Brigaud & Vasseur, 1989) and the coefficient of determination obtained, seems to be Model 4.2.6 (Equation 9). The adjusted coefficient of determination, R^2 is 0.882.

$$k_s = x(k_{qz}^{V_{qz}} \cdot k_{fsp}^{V_{fsp}} \cdot k_{ca}^{V_{ca}} \cdot k_{ka}^{V_{ka}} \cdot k_{s/I}^{V_{s/I}} \cdot k_{re}^{V_{re}}) + (1-x)(k_{>63}^{V_{>63}} \cdot k_{2-63}^{V_{2-63}} \cdot k_{<2}^{V_{<2}}) \quad (11)$$

where	x	-	ratio estimated from the mineralogical parameters = 0.24
	V_i	-	volume fraction of mineral and grain size fraction i ,
	k_{qz}	-	thermal conductivity of quartz = 6.82 W/m·K,
	k_{fsp}	-	thermal conductivity of feldspar = 3.49 W/m·K,
	k_{ca}	-	thermal conductivity of calcite = 3.62 W/m·K,
	k_{ka}	-	thermal conductivity of kaolinite = 2.80 W/m·K,
	$k_{s/I}$	-	thermal conductivity of smectite and illite = 1.61 W/m·K,
	k_{re}	-	thermal conductivity of remaining minerals = 3.43 W/m·K,
	$k_{>63}$	-	thermal conductivity of grain size fraction >63 μm = 5.79 W/m·K,
	k_{2-63}	-	thermal conductivity of grain size fraction 2-63 μm = 1.52 W/m·K,
	$k_{<2}$	-	thermal conductivity of grain size fraction <2 μm = 1.89 W/m·K.

CONCLUSION.

Thermal conductivities of unconsolidated sediments from the Vøring Basin, measured with a needle probe, range from 0.69 - 1.57 W/m·K. Comparative measurements of thermal conductivity with divided bar apparatus give lower thermal conductivity values. The difference between the measurements seems to be rather constant. The possibility that the difference may be due to systematic calibration error between the two methods, warrants further investigation.

A model which estimates thermal conductivity for unconsolidated sediments with a coefficient of determination, R^2 of 0.88 is developed. For these unconsolidated sediments water content is found to have the major influence on thermal conductivity, and a fairly good estimate of thermal conductivity can thus be made directly from the measurements of water content ($R^2=0.81$). Grain size fractions, and especially the content of the coarsest fraction (> 63 μm) strongly influence thermal conductivity, and is for these sediments a more important factor than the total mineralogy. Thus the model based on water content, grain size fractions and mineralogy was found to be the best, a simpler model based on the content of coarsest fraction (> 63 μm) and water content is suggested to be the preferable model for the thermal conductivity of these unconsolidated sediments.

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Paper 5

Paper 5

The effect of grain size on thermal conductivity of quartz sands and silts*.

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ABSTRACT

Synthetically samples of different grain size fractions of quartz were prepared and the thermal conductivities measured with a divided bar apparatus. The measurements were carried out on dried and water saturated samples both perpendicular and parallel to the main stress direction during compaction of the samples. A clear correlation was observed between the porosity and the measured thermal conductivities. For water saturated samples the thermal conductivity decreases more with increasing porosity than for ideal isotropic material as predicted by the geometric mean model. A clear positive correlation was also found between the thermal conductivity and the grain sizes of the samples. When the expected effect of porosity on the thermal conductivity was excluded, a linear correlation between the logarithm of the grain size and the measured thermal conductivities of the water saturated samples was found. An anisotropy effect ($a = k_v/k_h$) in thermal conductivity was observed for the samples, being most prominent for the coarsest ones. The measured anisotropy is assumed to be mainly due to the thermal anisotropic nature of the quartz crystal.

KEYWORDS: thermal conductivity, grain size, quartz samples,

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INTRODUCTION.

The three main factors influencing the thermal conductivity of sedimentary rocks are porosity, mineralogy and texture (e.g. Farouki 1981; Brigaud & Vasseur 1989; Midttømme *et al.* 1994). Of these factors, texture is the most difficult to take into account since it is the most complex. The grain size and the grain size distribution are important factors controlling the texture of sedimentary rocks. These factors are assumed to influence the thermal conductivity (Anand *et al.* 1971; Rzhovsky & Novik 1971; Brigaud *et al.* 1990; Beziat *et al.*, 1992; Griffiths *et al.* 1992; Jones & Pascal 1994; McKenna *et al.* 1996; Midttømme *et al.* 1997, 1998). Rzhovsky & Novik (1971) found a decrease in thermal conductivity with decreasing grain size of the material. Their measurements on quartz samples gave thermal conductivities in the range of 7.0 - 11.7 W/m-K for monocrystalline, 3.6 W/m-K for polycrystalline samples and 1.39 W/m-K for fused quartz samples. A similar trend was observed for marble and halite. These authors suggested a relationship between thermal conductivity and average grain size for certain rocks as follows:

$$k = k_0 \frac{d_{av}}{d_{av} + B} \quad (1)$$

where k_0 - thermal conductivity of a monocrystal,
 d_{av} - mean grain size (mm),
 B - ratio of the temperature gradient at a grain contact to the mean temperature gradient of the specimen as a whole (for marble $B \approx 0.027$ at 0 °C).

Thermal conductivities estimated by Equation 1 are plotted against the mean grain size in Figure 1.

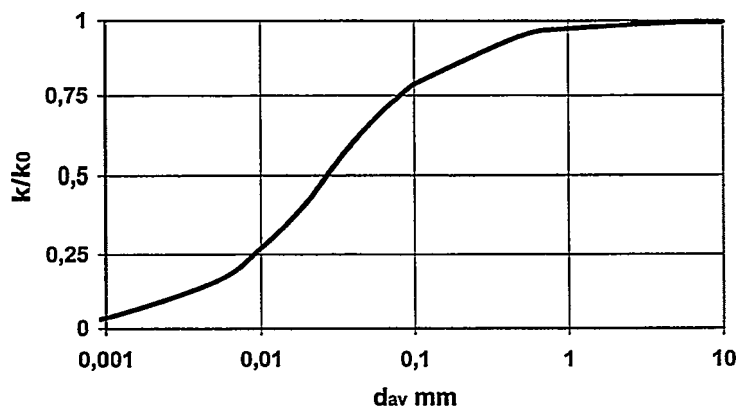


Figure 1. A curve estimated for marble from Equation 1, showing the dependence of thermal conductivity upon grain size d_{av} - mean grain size, k - thermal conductivity, k_0 - thermal conductivity of a monocrystal.

Figure 1 shows that the effect of grain size is most significant for fine-grained material. In a study of unconsolidated fine-grained sediments, the $> 63\mu\text{m}$ content was, excepting the water content, found to have greatest influence on the measured thermal conductivities (Midttømme *et al.* 1997). The dependence of grain size on thermal conductivity is assumed to be related to the number of grain contacts per unit path of heat flow (McGaw 1969; Rzhevsky & Novik 1971; Beziat *et al.*, 1992; Griffiths *et al.* 1992). The grain contact zones offer more resistance to the heat flow than the grains itself. This resistance, known as thermal contact resistance (Incropera & De Witt, 1990) leads therefore to a reduction in thermal conductivity with a decrease in the grain size of the material. McGaw (1969) and Griffiths *et al.* (1992) explained the reduction in heat flow caused by the increased number of grain contacts by thin fluid films between the grains.

Typical values of thermal conductivities measured at 20 °C for clay- and siltstones are 0.80 -1.25 W/m-K, and for sandstones 2.50 - 4.20 W/m-K (Blackwell & Steele 1989). Thermal conductivity values published by Clark (1966) vary in the range of 0.9 - 6.5 W/m-K for sandstones and 0.6 - 4.0 W/m-K for claystones. By modelling thermal conductivities from well log data from the Paris Basin, Demongodin *et al.* (1991) obtained a best fit model by using a matrix conductivity of 6.6 W/m-K for a sandstone matrix and 1.5 W/m-K for a clay matrix. Though these values show a correlation between the thermal conductivity and the grain size of sedimentary rocks, they can not be considered as confirmation of a grain size effect on the thermal conductivity, since the grain size will influence other factors such as porosity, permeability, mineralogy and specific surface area, which also will influence the thermal conductivity (Figure 2). In this case the influence of the grain size can be considered as a secondary effect, which will probably best be taken into account when considering the primary controlling factors.

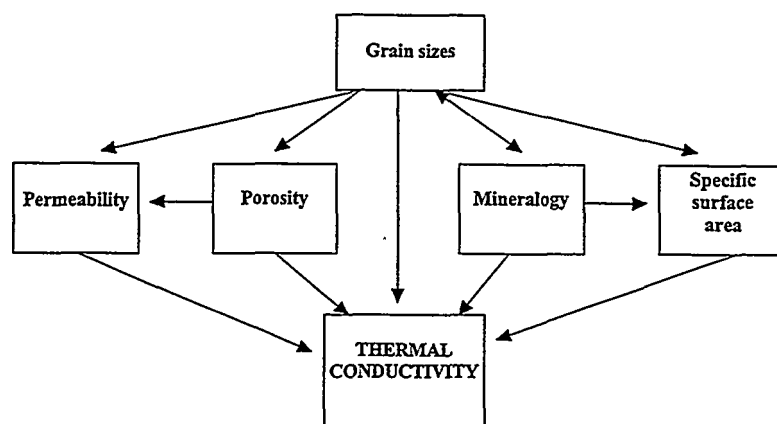


Figure 2. Flow diagram showing the primary and secondary effects of grain size on thermal conductivity.

Porosity is an important factor controlling thermal conductivity (e.g. Brigaud & Vasseur 1989; Griffiths *et al.* 1992). Pore fluids have a lower thermal conductivity than the matrix in sedimentary rocks. An increase in porosity will therefore lead to a decrease in the conductivity. At very shallow depths fine-grained have higher porosities than coarser grained sediments (North 1990), and for this reason lower thermal conductivities. At depths below 1.5 - 2.0 km sands and sandstones normally have higher porosities than shales (e.g. Rieke & Chilingarian 1974). The effect of grain size on porosity will be highest for unconsolidated sediments, since burial history and depth will greatly influence the porosity for consolidated sediments.

Mineralogy is as the grain size related to sedimentary facies. There will in general be a significant correlation between the mineralogy and the grain size. Most sandstones contain large amounts of quartz, which has a high thermal conductivity ($k_{\text{quartz}} = 7.7 \text{ W/m}\cdot\text{K}$). A high content of clay mineral is a characteristic property of claystones. The clay minerals have low mineral conductivities ($k_{\text{illite}} = 1.9 \text{ W/m}\cdot\text{K}$, $k_{\text{montmorillonite}} = 1.9 \text{ W/m}\cdot\text{K}$ and $k_{\text{kaolinite}} = 2.6 \text{ W/m}\cdot\text{K}$ (values from Brigaud & Vasseur (1989)). The higher thermal conductivities observed for sandstones than for claystones, may thus be explained from the mineralogy alone.

Mineralogically based models have been developed, where matrix conductivities are predicted from the mineralogical composition (Horai 1971; Johansen 1975; Brigaud & Vasseur 1989; Middleton, 1994; McKenna *et al.* 1996). Most of these studies have been carried out on sandstones. McKenna *et al.* (1996) restricted their study to clean sandstone samples, because of the lack of mudrock cores and the uncertainties related to the thermal conductivities of clay minerals. Brigaud & Vasseur (1989) found it impossible to make measurements on clay cores because of the practical problems related to the coring and sample preparation. They therefore prepared artificial samples to find the mineral conductivities of the clay minerals. In the studies by Pribnow & Umsonst (1993) and Midttømme *et al.* (1997, 1998) on fine-grained materials the mineralogical models estimate higher thermal conductivities than the measured values (Figure 3). Beziat *et al.* (1988) concluded that the mineralogical composition was less important in modelling thermal conductivities of clays compared to water content (i.e. porosity) and density.

The specific surface area is another factor which is strongly related to the grain size of the material. It might be difficult to distinguish between the influence of these two factors on the thermal conductivity. Johansen (1975) considered the grain size distribution of the material as a secondary factor to the specific surface area in controlling the thermal conductivity. The surface area effect was explained by the heat flow barrier arising from the water film coating the water wet mineral grains.

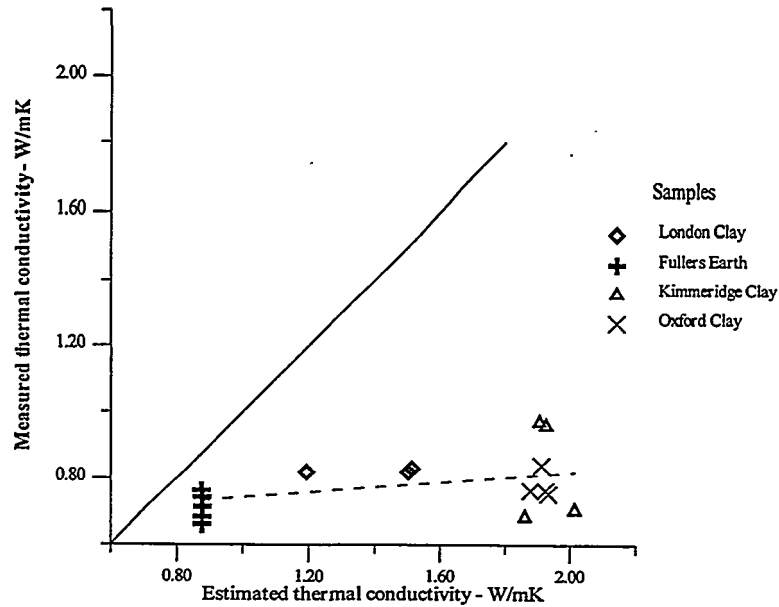


Figure 3. An example of lack of correlation between thermal conductivities estimated by a mineralogically based model and measured values. The solid line is the unity line (1:1). The dotted line is the regression line. The samples are mudstones from England (Midttømme *et al.* 1998).

Compared to most other minerals, clay minerals have an exceptionally large surface area caused by both large external and internal surface areas. The effect of the internal surface area on the thermal conductivity remains unclear, but is assumed to have little effect from the fact that smectite with extremely high internal surface area of 750 m²/g (van Olphen & Fripiat 1979) has similar mineral conductivity as illite, with an internal surface area of 5 - 10 m²/g. For clayey samples, the specific surface area certainly reflect the content of clay minerals. On the other hand, the content of clay minerals is strongly related to the grain size, since the finest fractions have the highest contents of clay minerals.

The grain size will also influence the *sizes, shapes and distribution of the pores*. The micro porosity of the most fine grained material will transfer heat differently than a more coarse grained system (Johansen 1975). The pore size distribution and pore interconnectedness determines the permeability of the material. The permeability as expressed by Kozeny's equation is as follows (e.g. North 1990):

$$k = \frac{\phi^3}{KS^2} \quad (2)$$

where	k	-	permeability,
	ϕ	-	porosity,
	K	-	Kozeny's constant,
	S	-	specific surface area.

Empirical thermal conductivity models have been developed with permeability as a variable (Zierfuss & van der Vliet 1956; Anand *et al.* 1973). By multiple regression analysis Anand *et al.* (1973) found a positive correlation between permeability and thermal conductivity of sandstones. They suggested that this correlation reflected the effect of grain size, since not only permeability but also thermal conductivity increased with increasing grain size of the material. Later Farouki (1981) concluded that the effect of permeability on thermal conductivity was related to the specific surface area.

Even the *shape of the grains* will influence the thermal conductivity of the material (Johansen 1975; Farouki 1981; Brigaud & Vasseur 1989; McKenna *et al.* 1996). Thermal conductivities measured on dry samples of crushed rocks have been found to be considerably higher than on sand of similar mineralogical composition (Kersten 1949, ref. in Farouki 1981). On the basis of empirical studies, Johansen (1975) proposed two equations for estimating thermal conductivity from dry density, one for natural sands and one for crushed rock. At the same dry density the crushed rock samples gave the highest thermal conductivity.

Anisotropy of thermal conductivity.

A further point of uncertainty in determination of thermal conductivity is the anisotropy effect. Thermal conductivities measured parallel (k_{\parallel}) to the layering are in general higher than those measured perpendicular (k_{\perp}). The anisotropy ratio is defined as:

$$a = \frac{k_{\parallel}}{k_{\perp}} \quad (3)$$

The anisotropy of thermal conductivity correlates with the structural-textural properties of sedimentary rocks and the orientation of the minerals. Sand and limestones usually show only a small anisotropy ($a < 1.3$). The most anisotropic rocks are shales and claystones ($a < 4.0$) (Schön 1996). Schön (1996) proposed three causes for the anisotropy:

1. crystal anisotropy of the individual rock forming minerals,
2. intrinsic or structural anisotropy resulting from the mineral shapes and their textural arrangement,
3. orientation and geometry of cracks, fractures and other defects.

Measurements of the anisotropy of minerals published by Cermak and Rybach (1982) show highest anisotropy for the sheet silicates. The anisotropy of muscovite was 6.1 ($k_{\perp} = 0.84$ W/m·K, $k_{\parallel} = 5.1$ W/m·K). A considerable anisotropy was also measured for quartz ($a = 1.74$, $k_{\perp} = 6.5$ W/m·K, $k_{\parallel} = 11.3$ W/m·K). When the grains are randomly oriented in the matrix, the effect of mineral anisotropy has little effect on the anisotropy of the thermal conductivity of the rock, but when the minerals show a preferential orientation the thermal conductivity becomes anisotropic (Demongodin *et al.* 1993).

Modelling the thermal conductivity.

Different models of thermal conductivity have been developed (Farouki 1981; Somerton 1992; Midttømme *et al.* 1994; Schön 1996). One of the most successful models is the geometric mean model. This model is among others used by Brigaud & Vasseur (1989); Middleton (1994) and McKenna *et al.* (1996). This simple model is in many cases found to be better than more sophisticated models used to calculate the thermal conductivity of sediments (Demongodin *et al.* 1991). The basic geometric mean equation applied to sedimentary rocks is:

$$k = k_s^{1-\phi} \cdot k_f^{\phi} \quad (4)$$

where	k	-	thermal conductivity of sample, W/m-K,
	k_s	-	thermal conductivity of matrix, W/m-K,
	k_f	-	thermal conductivity of fluid, W/m-K,
	ϕ	-	porosity (0.00 - 1.00).

Two other basic models, the arithmetic and harmonic mean models, are also widely used (Somerton 1992; Pribnow & Umsonst 1993; McKenna *et al.* 1996). These models are based respectively on parallel and series arrangement of the components relative to the direction of heat flow. The values estimated by these models give boundary values of thermal conductivity of the material. For more isotropic samples the geometric mean model would theoretically be most correct (Midttømme & Roaldset, 1998).

MATERIAL AND METHODS.*Sample preparation.*

Synthetically quartz silt- and sandstone samples were prepared from Vatne quartz, a hydrothermal quartzite with a purity above 99.9 % quartz from Vatne in northern Norway. The material was crushed and separated into different size fractions by sieving and sedimentation. The grains are characterized by an elongated and angular form (Figure 4). The synthetic rock samples were prepared according to the method in Holt & Kenter (1992) and Holt *et al.* (1993). The different fractions were mixed with a sodium silicate solution ($\text{Na}_2\text{Si}_2\text{O}_5$) with compositions varying from 16 g quartz/ml Na-Si-solution for the coarsest to 8.3 g quartz/ml for the finest fractions. The material was packed in a cylindrical form ($d = 4.2$ cm), then compacted in a triaxial cell at uniaxial stress conditions of 10 ton (4.2 MPa) for 5 minutes before hardening by standing for 6 minutes in an atmosphere of CO_2 . The synthetic rocks were then cut into 3.0 cm cubes (Figure 5). Two samples of Ottawa sand, a rounded quartzitic beach sand, were prepared by the same method, and included in this study.

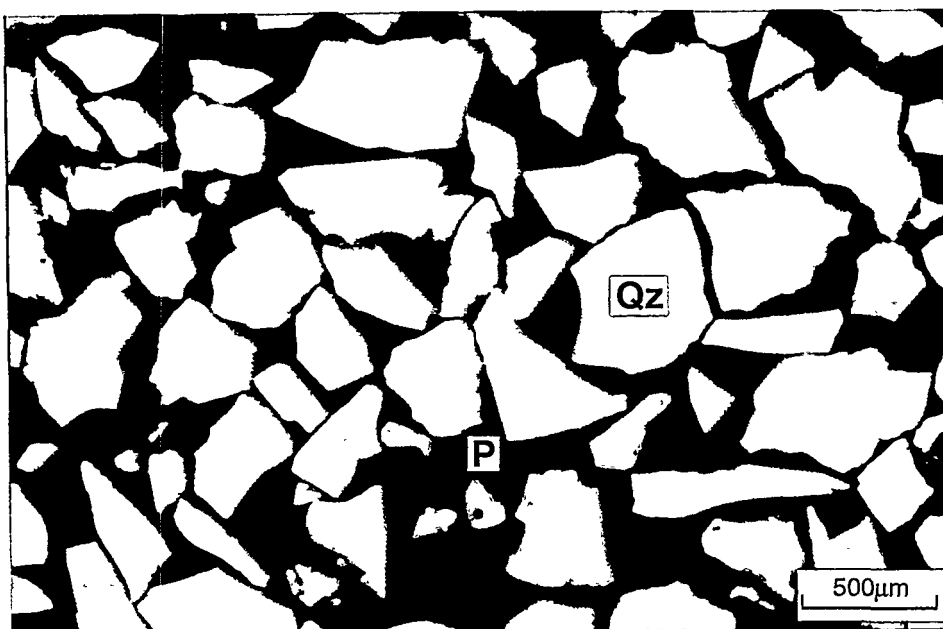


Figure 4. Thin section micrograph of crushed grains of Vatne quartz, fraction 250 - 500 μm .
Qz - quartz, P - pore.

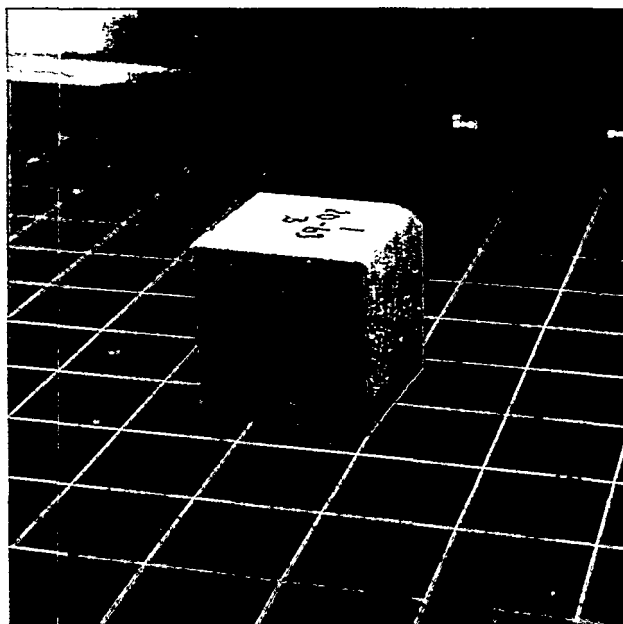


Figure 5. Photo of a synthetic rock cube, $l = 3 \text{ cm}$.

Measurements of thermal conductivities.

Thermal conductivities were measured with a divided bar apparatus, developed at the Institute of Refrigeration, Norwegian University of Science and Technology (Brendeng & Frivik 1974). This apparatus was originally designed for bigger samples. Test measurements on samples of different sizes have shown the measured values to be up to 3.5% lower for cubes of this size ($l = 3.0$ cm) than for the larger ones ($l = 40.0$ cm, $h = 10.0$ cm) (H. Johansen, unpublished 1992). Repeated measurements on the massive quartzite (sample B) gave an experimental error within 2.5 %. The synthetic quartz cubes were measured in both water saturated and dried samples, both perpendicular and parallel to the main stress direction. The samples were water saturated by standing in a water vapor atmosphere in a desiccator for one day. The samples to be investigated in dry state were dried at 103 °C for at least one day before the measurements were carried out. During measurements the mean temperatures of the sample were in the range of 23 - 29 °C and the temperature gradients over the sample varied from 0.8 - 4.7 K.

The porosities were estimated from the dry weight of the cubes.

RESULTS.

The thermal conductivity measurements are presented in Table 1 and Figures 6 and 7. The synthetic rock cubes fell into three groups, according to their quality (Table 1). Only those which are ranked in group I and II are considered in the further discussion. The reduced quality for some of the samples were mainly due to problems during preparation. A layering texture developed perpendicular to the main stress direction for the samples of the finest fractions. This feature occur because the samples were compacted in thin layers during the preparation process. Attempts to prepare samples of < 2 μm fraction failed because of this layering problem. A problem with the samples coarser than 0.25 mm was to cut them into cubes. Grains easily fell out, and made a rough cutting surface. This problem was most prominent for the Ottawa sand samples. The most perfect cubes were obtained for the grain size ranges 6-20 μm and 20-63 μm . The low weights measured on the wet 2-6 μm samples suggest that they were not 100 % water saturated.

Table 1. Measured thermal conductivities. The measurements are carried out at temperatures in the range 23 - 29 °C.

Sample	Quality of the samples ¹	Weight g Dry/Wet	Porosity %	Thermal conductivity W/m·K						Anisotropy a=k /k _⊥	
				Dry			Wet			Dry	Wet
				⊥	II	Mean	⊥	II	Mean		
<i>Valne quartz</i>											
2- 6µm A	II	40.0 / 49.0	44	0.49	0.55	0.52	1.12	1.47	1.29	1.11	1.31
2- 6µm B	II	41.7 / 49.6	42	0.50	0.61	0.56	1.07	1.16/1.04	1.12	1.23	1.08/0.97
6 - 20µm A	I	43.4 / 53.7	39	0.68	0.69/0.69	0.68	1.44	1.52/1.55	1.50	1.02/1.02	1.06/1.08
6 - 20µm B	I	42.7 / 52.2	40	0.68	0.70	0.69	1.57	1.47/1.52	1.52	1.03	0.94/0.97
20 - 63 µm A	I	45.7 / 55.4	36	0.64	0.65/0.66	0.65	1.70	1.63/1.68	1.67	1.00/1.03	0.96/0.99
20 - 63 µm B	I	42.5 / 52.8	41	0.46	0.44	0.45	1.43	1.43/1.39	1.42	0.98	1.00/0.98
0.25 - 0.5mmA ²	II	36.9 / 44.3	38	0.83		0.83	1.77		1.77		
0.25 - 0.5mm B	I	46.4 / 52.9	35	1.05	1.08	1.07	1.63	1.65/1.98	1.75	1.03	1.01/1.21
0.6 - 0.83 mm A	II	46.4/ 54.0	35	1.02	1.01/1.06	1.03	1.73	1.51/1.69	1.65	0.99/1.04	0.88/0.98
0.6 - 0.83mmB ³	III	44.8/50.8	37	0.70	0.83	0.76	1.22	1.47/1.59	1.43	1.19	1.20/1.31
2 - 4 mm	I	52.2/56.4	27	1.26	1.45	1.36	1.86	2.15/2.19	2.19	1.15	1.15/1.18
Massive A	I	70.8 / 70.8	0	4.22	4.15/4.44	4.27		4.18		0.98/1.05	
Massive B	I	70.6 / 70.6	0	3.76	3.96/4.65	4.12				1.05/1.24	
<i>Ottawa sand</i>											
0.6-0.83 mm A	III	41.8/					1.88				
0.6-0.83 mm B	III	42.9/49.0					1.48				

¹The samples are grouped into three groups according the quality of the cubes, I; good, II; some defects that might influence the measurements, III; bad, the results are not considered in the discussion.

²Size of sample 0.25-0.5mm A: 2.5*3.0*3.0 cm³.

³Contains a through-going parallel fissure.

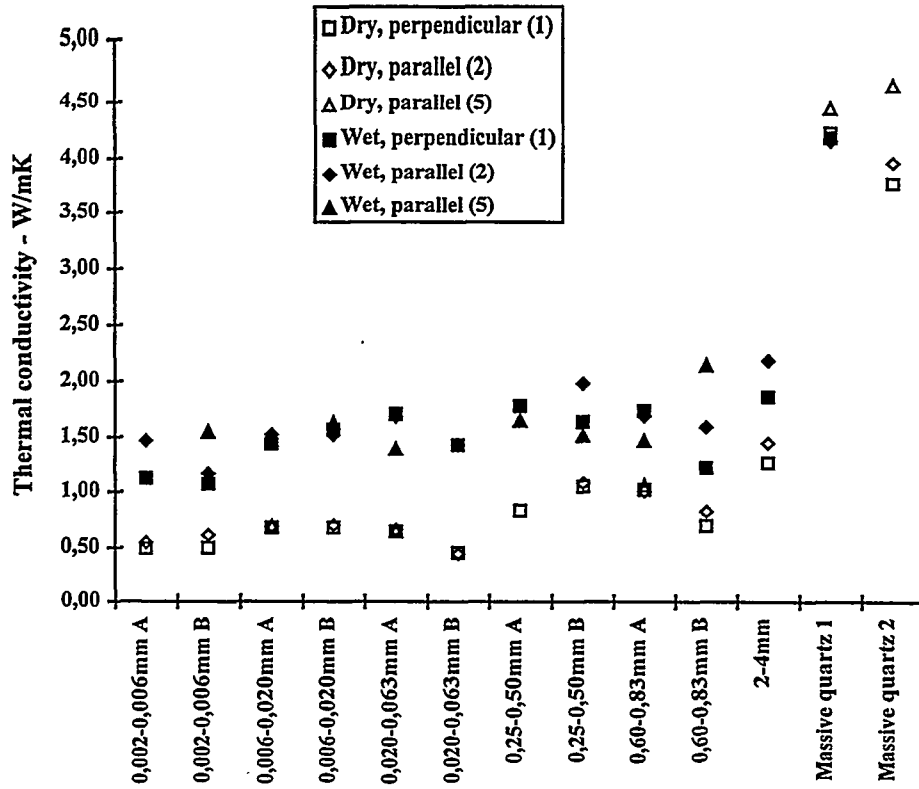


Figure 6. Measured thermal conductivities of the Vatne quartz samples.

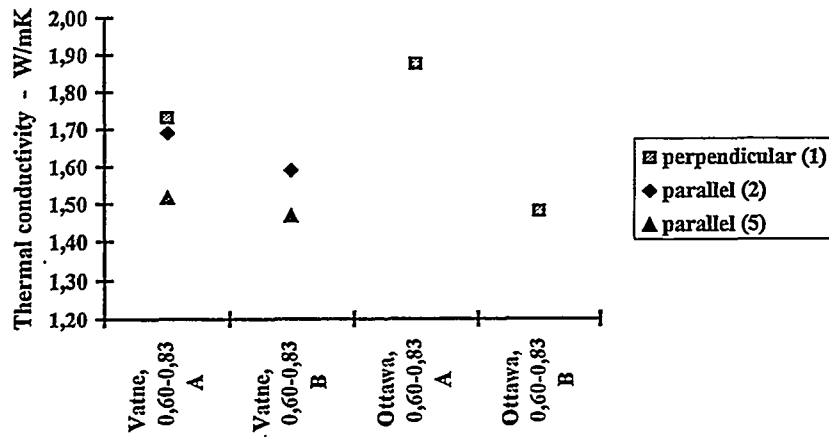


Figure 7. Measured thermal conductivities of the 0.60-0.83 mm fractions.

DISCUSSION.

The effect of porosity on thermal conductivity.

The correlation between the porosity and the measured mean thermal conductivity is shown in Figure 8, where an increase in the porosity from 27 % to 44 % gives a decrease in the measured thermal conductivities of water saturated and dried samples of 0.88 W/m·K (-40 %) and 0.84 W/m·K (-62 %), respectively. This negative correlation between thermal conductivity and porosity may be explained by the fact that porosity (see Figure 2)

1. directly influences the thermal conductivity, i.e. is a primary factor controlling the thermal conductivity of the rock,
2. is related to factors as the grain size, which will influence the thermal conductivity, (Porosity can in this case be considered as a secondary factor controlling the thermal conductivity.)
3. will affect properties such as the permeability, which again will influence the thermal conductivity.

To test the primary influence of porosity on the thermal conductivity we have estimated the thermal conductivity by use of the isotropic model based on the geometric mean equation. Since the matrix consists of pure quartz the samples can be considered as a two-component material with a pore system filled by water or air and a matrix of quartz. Thermal conductivity of the pore fluid, k_p , was set as a constant to 0.60 W/m·K for water saturated samples and 0.024 W/m·K for dried samples. Matrix conductivity, k , was determined by nonlinear regression analysis based on measured thermal conductivity versus porosity. The best fit model for the measured thermal conductivities for water saturated samples was:

$$k = 2.86^{(1-\phi)} \cdot 0.60^\phi \quad (5)$$

with a coefficient of determination, R^2 , of 0.57. For the dried samples the best model obtained was:

$$k = 6.21^{(1-\phi)} \cdot 0.024^\phi \quad (6)$$

with a coefficient of determination, R^2 , of 0.81. These models are plotted with solid and dotted lines in Figure 8. An estimate of thermal conductivities of the dried samples can be made by the geometric mean model, but this model does not satisfactorily predict the measured variation in thermal conductivity for the water saturated samples. A lower influence of the porosity on the thermal conductivity of the water saturated samples is seen by using the geometric mean model rather than from the trend given by the measurements. The matrix conductivity given by the best fit model for water saturated samples is; $k_s = 2.86$ W/m·K. This value is unrealistically low compared to the thermal conductivities measured on the massive quartz samples A and B, $k = 4.27$ W/m·K and $k = 4.12$ W/m·K, respectively and the fact that thermal conductivity of quartz is; $k_{\text{quartz}} = 7.7$ W/m·K.

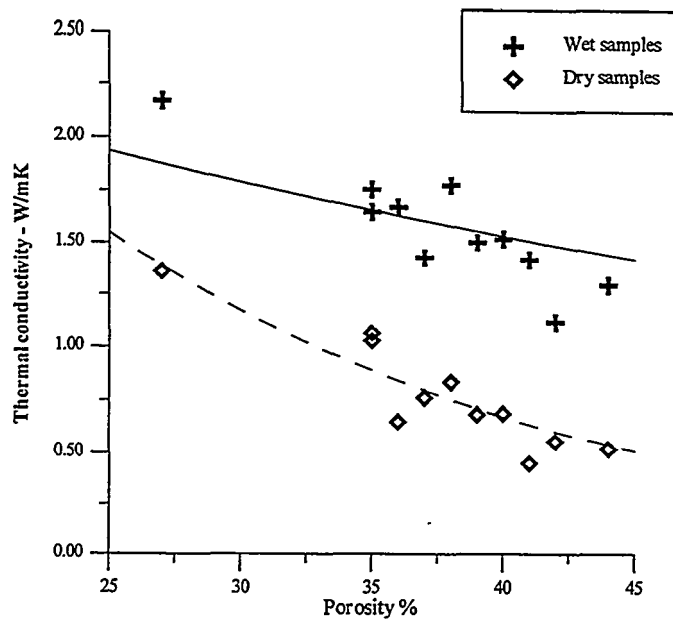


Figure 8. Mean thermal conductivities plotted against porosity. The best fit geometric mean models for wet and dry samples are shown with respectively solid and dotted lines. The coefficients of determination are for the wet samples; $R^2 = 0.57$ and for dried samples; $R^2 = 0.81$.

Though other models like the anisotropic model based on the harmonic mean equation, will fit our data better than the geometric mean model (Midttømme & Roaldset 1998), we will continue using the geometric mean model. Instead of introducing other models, the matrix conductivity, which represents the matrix properties, will be focused on further in the discussion.

The effect of grain size on thermal conductivity.

Table 1 show that for this material the porosity decreases as the grain size increases. The correlation obtained between porosity and thermal conductivities measured for the water saturated samples might thus be due to the effect of grain sizes on the thermal conductivity. The permeability may also influence the thermal conductivity. This effect is assumed to be taken care of by considering both the effects of porosity and the grain size. A correlation seem to exist between mean thermal conductivity and mean grain size for both dried and water saturated samples (Figure 9). To omit the effect of porosity, the matrix thermal conductivity, k_m , is calculated by the inverse of the geometric mean model (Equation 4) and for water saturated samples plotted versus the grain size in Figure 10.

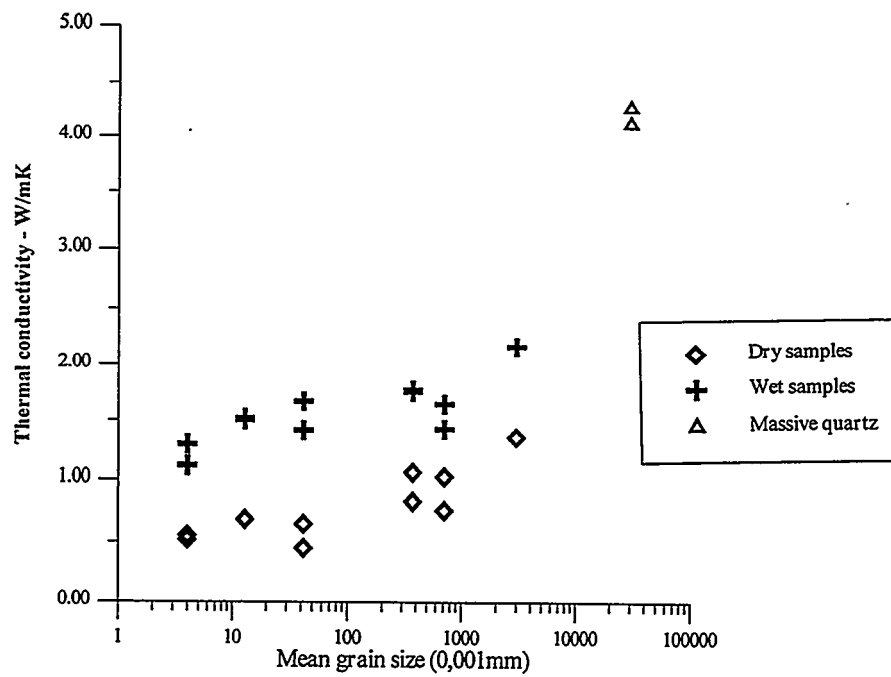


Figure 9. Mean thermal conductivities plotted against the mean grain size of the samples.

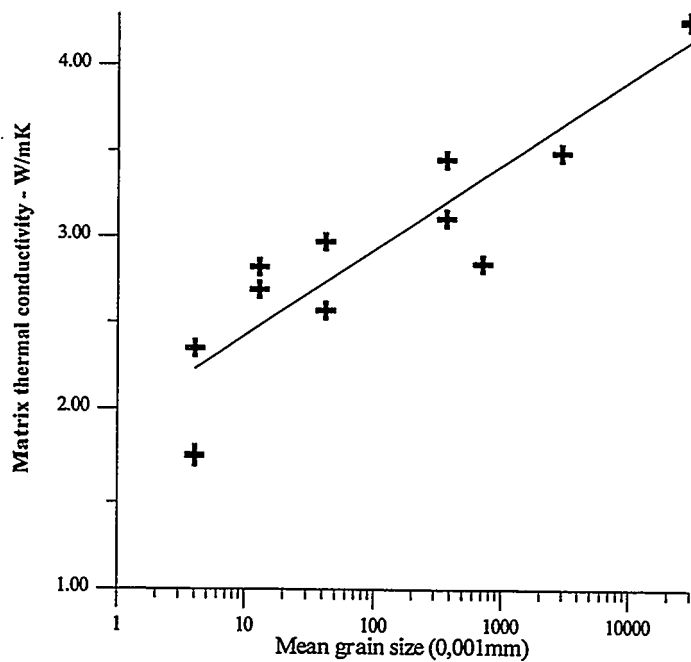


Figure 10. The calculated matrix conductivity for water saturated samples plotted versus the mean grain size of the samples. The solid line shows the logarithmic regression, $R^2 = 0.86$.

The best model of matrix conductivity (Equation 7) is indicated by a linear correlation between the calculated matrix conductivities and the logarithm of the grain sizes since the influence of grain size was great for the finer and less for the coarse material. The coefficient of determination, R^2 , for this model is 0.86.

$$k_s = 0.215 \cdot \log(d_m) + 1.93 \quad (7)$$

where k_s - matrix conductivity (W/m·K),
 d_m - mean grain sizes of samples (μm).

Are the thermal conductivities for natural samples a function of grain size?

As only the grain size effect on synthetic and not on natural samples has been considered here, we will pay attention to the relevance of data on synthetic samples for natural samples.

- As natural samples normally show wider range of grain size, the grain size distribution will be more important factor than the mean grain size. The grain size effect on the thermal conductivity will certainly be different for a bimodal clayey sand and an unimodal silt even when their mean grain sizes are equal. The mean grain size for natural samples is therefore an ambiguous parameter for modelling the thermal conductivity. By using a set of factors describing the grain size and the grain size distribution of the material more realistic thermal conductivity models can be developed.
- The grain size and mineralogy of natural sediments are interrelated in a complex manner. By using synthetic quartz samples we have avoided taking account of complexing factors. Since most minerals and in particular clay minerals, have lower mineral conductivities than quartz, the grain size effect caused by a decrease in grain sizes of these minerals is expected to be lower than for quartz. An exact calculation of the thermal conductivity requires a description of mineralogy, size and textural arrangements of the mineral grains.
- To which extent the grain shape influence the thermal conductivity needs further investigations as the comparative measurements carried out in this work on similar fractions of crushed Vatne quartz and rounded Ottawa sand (Figure 7) suffered from preparation problems. Shape will certainly influence the specific contact area for the grains, and therefore affect the thermal conductivity. This grain shape effect is assumed to be more prominent for the coarser than for the finer grains, since coarser grains have higher thermal conductivity and are therefore more sensitive to changes in shape than finer grains.
- By using synthetic samples we have omitted diagenetic effects. Diagenesis is considered to be an important factor controlling the thermal conductivity in sedimentary basins. Diagenetic mineral reactions will, in particular, in the cases of intense quartz cementation, strongly affect

the contact zones between the grains and the preferable pathways of heat transfer. These factors should be better studied and included in future thermal modelling.

The thermal conductivity for sedimentary rocks as indicated for the synthetic silt- and sand cubes investigated here, seems to be a logarithmic function of the grain size, with highest effect for the finest grain fractions.

Anisotropy.

We have so far ignored the effect of anisotropy on the thermal conductivity by using a mean value of perpendicular and parallel thermal conductivity. The anisotropy of the measured thermal conductivities ($a = k_{\parallel}/k_{\perp}$) vary in the range 0.88 to 1.31 (Table 1). The finest and the coarsest samples show the highest variation. The observed thermal anisotropy is assumed to reflect two effects:

1. Quartz is anisotropic mineral with the highest thermal conductivity parallel to the crystallographic c-axis. This may explain the anisotropy measured for the two massive quartzite and the coarsest crushed samples. For the finest grained material this crystallographic effect are subordinate and can be ignored compared to the effect of grain size.
2. For the finest samples, a weak layering arising perpendicular to the main stress during the preparation of the cubes may explain the anisotropy measured for the dry samples of size ranges 2-6 μm and 0.6 - 0.83 mm. This textural effect will lower the perpendicular, but influence less on the parallel measurements.

CONCLUSION.

An effect of grain size on the thermal conductivities of artificially prepared samples of crushed quartz is demonstrated. This effect is highest for the finest grained samples. It is therefore concluded that grain size has an important influence on the thermal conductivities of sedimentary rocks, and as a consequence of this; grain size and grain size distribution are important factors in modelling and predicting thermal conductivity, particularly for shales and mudstones. The weak thermal anisotropy measured mainly for the coarsest grained quartz cubes is assumed to be related to crystal structure of quartz and its highest thermal conductivity parallel to the crystallographic c-axis.

ACKNOWLEDGEMENTS.

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Paper 6

Paper 6

Sensitivity of thermal conductivity for temperature history of sedimentary basins : a case study from the northern North Sea *

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ABSTRACT

The temperature in a sedimentary basin is highly influenced by the thermal conductivity of the sedimentary rocks. The objective of this study is to show how the variation in estimated vertical thermal conductivity may effect the estimated temperature history of a sedimentary basin. Four cases of temperature histories are selected for comparison. The modelling was carried out with the basin modelling programme BMT. The estimated temperature histories are most affected by the thermal conductivity model itself. The comparison cases show that the models give very different results. The number of parameters used in the models seems to have less importance for the modelled temperature history: Simplified thermal conductivity models based on lithology or both porosity and lithology appear to give comparable temperature histories to more advanced models based on a combination of mineralogical composition and porosity. A model where matrix conductivity is determined from measured thermal conductivities based on the mineralogy gives considerably higher temperatures than a model where matrix conductivity is estimated from the mineralogy by the geometric mean model. A grain size correction of this geometric mean model for the shale units gives comparable thermal histories with the model based on measurements. The temperature histories estimated from the mineralogy and porosity by three mixing law models give very different results. For example, the modelled present temperature within the Jurassic sediments at about 5150 m b.s.b varies from 90 °C by using the arithmetic mean model to 160 °C by using the harmonic mean model.

* In manuscript.

INTRODUCTION.

Thermal conductivity of sedimentary rocks is a key parameter in temperature modelling, because it controls the conductive heat flow, the main mechanism of heat transfer in sedimentary basins. The thermal gradient by conduction is described by Fourier's law as inversely proportional to the thermal conductivity for a given heat flow (Equation 1).

$$q = k \frac{dT}{dz} \quad (\text{Eq.1})$$

- q - heat flow (mW/m²),
 k - thermal conductivity (W/m·K),
 dT/dz - temperature gradient (K/m).

In basin modelling the thermal conductivity in general has to be estimated. The accuracy of the estimate depends on the rock information available, the accuracy of this information and the knowledge of how the rock parameters effect the thermal conductivity. Thermal conductivity of water-saturated sediments depends mainly on porosity, mineralogy and texture. The individual effects of these factors are still uncertain.

Three statistical mean models of thermal conductivity, the arithmetic (Equation 2), geometric (Equation 3) and harmonic mean (Equation 4) models have dominated recent thermal conductivity studies.

$$k = \phi k_f + (1 - \phi) k_s \quad (\text{Eq.2})$$

$$k = k_f^\phi \cdot k_s^{(1-\phi)} \quad (\text{Eq.3})$$

$$\frac{1}{k} = \frac{\phi}{k_f} + \frac{(1-\phi)}{k_s} \quad (\text{Eq.4})$$

These models, known as mixing law models (Somerton, 1992), combine values of the thermal conductivity of the rock matrix (k_s) with the conductivity of the pore fluid (k_f) on the basis of porosity (ϕ). The harmonic and arithmetic mean models are based on parallel and series arrangement of the components relative to the direction of heat flow. The geometric mean model estimates a mean value of harmonic and arithmetic mean. There are different opinions regarding which of these three mean models is the most correct (e.g. McKenna et al., 1996; Midtømme & Roaldset, 1997a).

Lack of adequate lithology information is a major restriction in basin modelling. The simplest thermal conductivity model, where thermal conductivity is set as a constant value or as a function of porosity, is therefore generally applied. The advantage of using more advanced models might be lost by using doubtful input data.

Lack of mutual correlation between modelled and measured thermal conductivities of shale and claystones has been demonstrated (Blackwell and Steele, 1989; Demongodin et al., 1991; Midttømme et al., 1997a,b). For selected clay- and mudstones from England thermal conductivities estimated by a mineralogically based geometric mean model were up to 170% higher than those measured (Midttømme et al., 1997a). A grain size effect is shown on the measured thermal conductivity where samples of grain sizes of clay and silt fractions have lower thermal conductivity than those of sand fraction (Rzhevsky, & Novik, 1971; Midttømme & Roaldset, 1997b). This grain size effect is assumed to be the main reason for the lack of expected correlation between the mineralogical models and the measurements.

Since there is a lack of reliable temperature observations in sedimentary basins, and all these temperature measurements represents today situation, we do not know the correct temperature history. Techniques and approaches for indirectly gaining present temperature or paleotemperature are developed, of which the most applied is the vitrinite reflectance (e.g. McCulloh & Naeser, 1988). Most of these techniques are analytical or observational in nature and therefore restricted by the need of samples of rock or pore fluid. The information obtained from these techniques is today not sufficient to reconstruct the thermal history of the sedimentary basins. Since we do not know the thermal histories better it is difficult to draw any conclusion about the best thermal conductivity model. The objective of this study is therefore to show how variation in estimated vertical thermal conductivity affect the temperature history of a sedimentary basin. This effect is exemplified by studying a section across the northern North Sea (Figures 1 & 2). The case study has been simplified to distinguish the thermal conductivity effect from other effects influencing the estimated temperature. Heat flow is an important factor controlling the temperature in the sedimentary basin (e.g. Gallagher et al., 1997), (Equation 1). The heat flow across the profile and through geologic time is kept constant at 50 mW/m². Obviously, this is an oversimplification for the study area but adequate for the objectives.

MODELLING TOOL

The modelling was carried out with the BMT (Basin Modelling Toolbox) program, a trademark of Geologica. This is a system for 2D geological, geophysical and geochemical modelling, and is divided into five modules, the geohistory, isostasy, tectonic, temperature and maturation modules (Lander et al., 1994). In this study mainly the geohistory and temperature modules are used.

CROSS-SECTION.

The seismic cross-section selected is 270 km long and extends from the Horda Platform, across the Viking Graben, continuing to the north-west (Figure 1). This section has also been used in a study of the effect of glaciation on the temperature regime in a sedimentary basin (Johansen et al., 1995). The geological history of the area is discussed by Bergsager (1986) for the pre-Tertiary and Rundberg (1991) for the Tertiary sections.

To show the effect of the thermal conductivity on temperature history, three points in the cross section from the Viking Graben are selected (Figure 2). These points represent depths within the lower Tertiary section (depth = 1650 m b.s.b.), the upper Jurassic shale section (depth = 5150 m b.s.b.) and the Permian section (depth = 8600m b.s.b.).

GEOHISTORY.

The evolution of the basin along the cross-section was reconstructed, taking into account the progressive compaction of the sediments, under the assumption of steady-state porosity/depth trends and preservation of the volume of the solid matrix during compaction (Fjeldskaar et al., 1993).

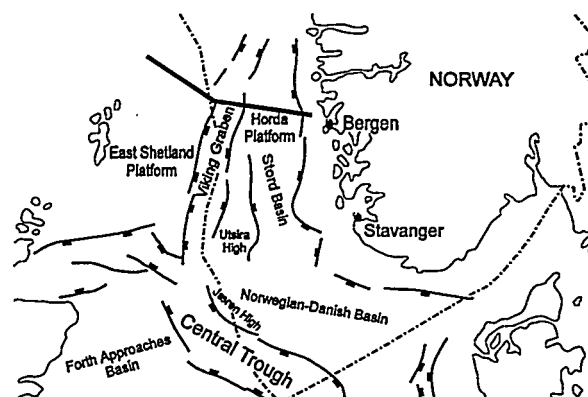


Figure 1. Location map. The cross-section selected for this study is shown by the solid line running NW-SE to WNW-ESE (Johansen et al., 1995).

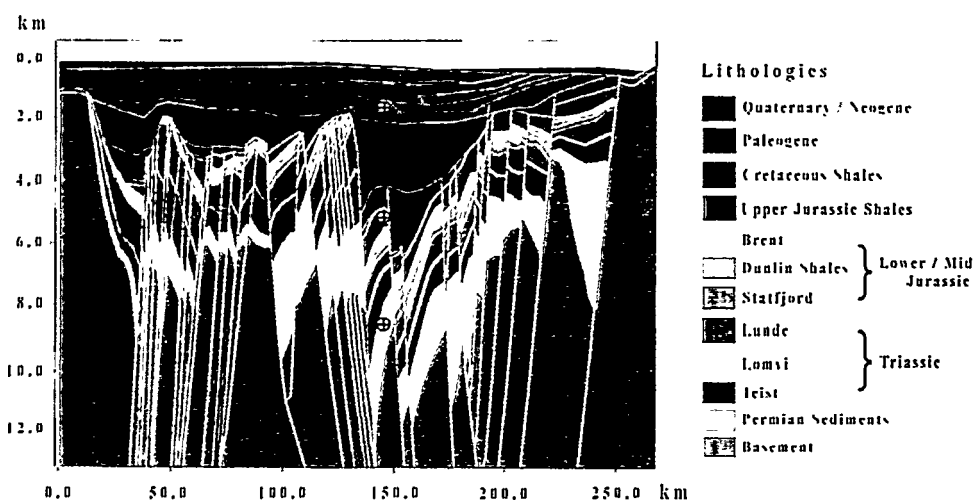


Figure 2. Cross-section along the section shown on the location map (Figure 1). The three points representing respectively the Tertiary, Jurassic and Permian sediment sequences are shown.

INPUT DATA.

Vertical thermal conductivity is determined by six different models (Table 1). Since heat is transferred radially from the earth interior, knowledge about the vertical component of the thermal conductivity is most important. In the following discussion, thermal conductivity refers to the vertical thermal conductivity. *Horizontal thermal conductivity* is determined by the BMT program and does not vary with the different thermal conductivity models. In all models thermal conductivity of the basement is taken as constant, $k_{\text{basement}} = 3.0 \text{ W/m}\cdot\text{K}$.

The *porosity* of the sediments is estimated by the BMT based on porosity-depth curves. The curves are specified by the surface porosity and an exponential decay constant. The data used are typical North Sea data (Sclater & Christie, 1980). The estimated porosity is shown in Figure 3.

The *mineralogy* is estimated from XRD analyses of samples of the formations taken from wells on or close to this section. The mineralogy, shown in Table 2, is an estimate, but compared to most other basin studies, probably is based on a larger data set.

The *heat flow* and *surface temperature* are kept constant across the section and through time at 50 mW/m² and 5 °C respectively. Heat is in this study only transferred by conduction.

Table 1 Thermal conductivity models.

	Function of	Model of thermal conductivity (k)	Model of matrix conductivity (k _m)	Values of conductivity	
				k _s	k _r
1	No (constant values)	No	No	k _{s(shale)} =1.5, k _{s(sandstone)} =2.5	
2	Porosity	Geometric mean	No (constant values)	k _{s(shale)} =2.0, k _{s(sandstone)} =3.5	0.6
3	Mineralogy, porosity	Geometric mean	BMT (mineralogy)		0.6
4	Mineralogy, porosity	Geometric mean	Geometric mean	Table 3	0.6
5	Mineralogy, porosity	Arithmetic mean	Geometric mean	Table 3	0.6
6	Mineralogy, porosity	Harmonic mean	Geometric mean	Table 3	0.6

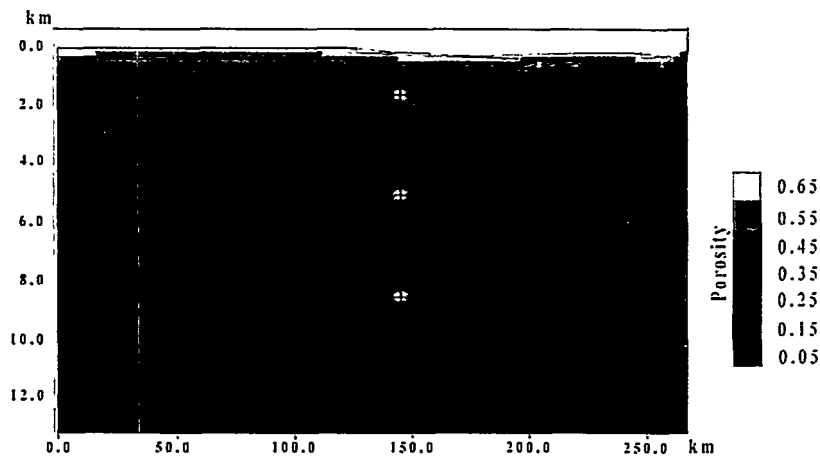


Figure 3. Porosity of the cross section, estimated by the BMT program.

Table 2 Mineralogy of the formations.

Section	Quartz	Alk. Fsp.	Plag	Mica	Chlorite	I/S	Kaolinite	Calcite	Dolom.	Siderite	Pyrite	TOC
Quaternary/ Neogene	35	6	5	16	7	7	23	1				
Paleogene	29	2	6	18	10	9	22	3			1	
Carbonaceous Shale	20	2	6	21	8	8	34					
Upper Jurassic Shale	25	7	7	10	3	10	25	5	1	1	4	2
Brent	31	5	6	8	2	5	27	5		2	3	6
Dunlin Shale	24	5	7	12	3	5	37	1		1	4	1
Statfjord	29	7	16	7	2	2	34				2	1
Lunde	30	15	25	2	1		8	14	2	1	1	1
Lomvi	30	15	25	2	1		8	14	2	1		
Teist	30	15	25	2	1		8	14	2	1		
Permian Sediments	21	21	19	6	5	1	1	1	21		3	1

Table 3. Thermal conductivity of common minerals in sedimentary rocks (Horai, 1971).

Mineral	Thermal conductivity W/m-K
Quartz	7.8
Calcite	3.4
Dolomite	5.1
Anhydrite	6.4
Pyrite	19.2
Siderite	3.0
K-feldspar	2.3
Albite	2.3
Mica	2.3
Halite	6.5
Kaolinite	2.8
Illite	1.8
Mixed layer I/S	1.9
TOC ¹	0.5

¹ Thermal conductivity from BMT database

RESULTS AND DISCUSSION.

Four comparative case studies of temperature histories estimated by six different thermal conductivity models given in Table 1 are considered.

Case study 1 - The effect of simplified thermal conductivity models.

Temperature histories are modelled from thermal conductivities estimated by Models 1,2 and 3 in Table 1 are shown in Figure 4. Model 1 is the simplest one. In this model the thermal conductivity is considered to be constant through the sections. Thermal conductivity is for the shale units set as 1.5 W/m-K and for the sandstone units as 2.5 W/m-K. In Model 2 the matrix conductivity is considered to be constant through the sections, respectively 2.0 W/m-K for the shale units and 3.5 W/m-K for the sandstone units. Thermal conductivity is estimated by the geometric mean model based on the estimated porosity data. Thermal conductivity is in Model 3 estimated by the geometric mean model from the mineralogy and porosity. Matrix conductivity is modelled by partial least square regression on the basis of a large database (TCD) of measurements on mineralogy and thermal conductivity. This matrix conductivity estimation is carried out by the BMT.

For the point representing the Permian a deviation up to 30 K is shown between the simplest model (Model 1) and the most advanced model (Model 3). The porosity model (Model 2) gives up to 10 K lower temperature for the Permian than the Model 3. There are only small deviations between

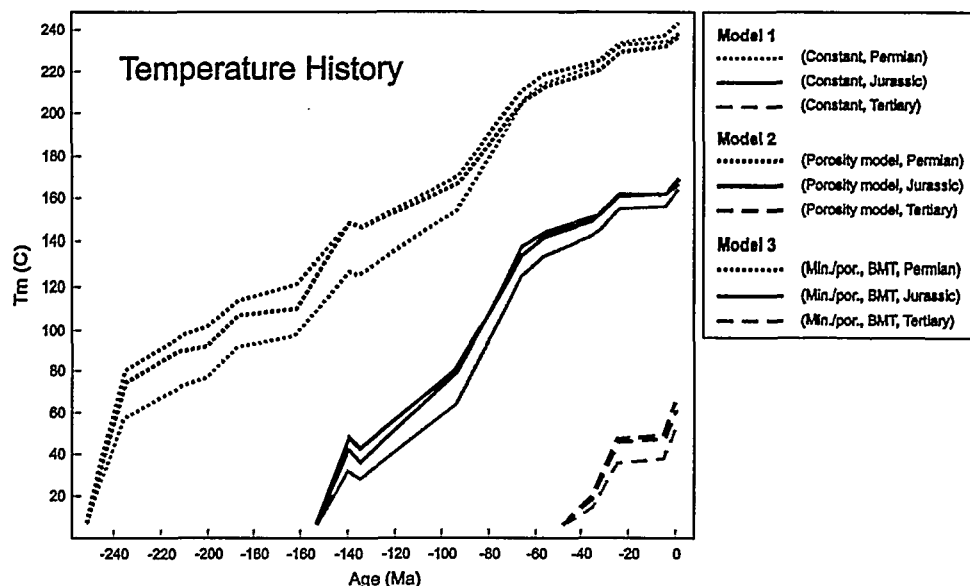


Figure 4. Case study 1. Temperature histories estimated by the two simplest thermal conductivity models (Models 1 & 2) and a model based on thermal conductivity measurements (Model 3).

these two models for the Jurassic and Tertiary points. This comparative case study shows a certain effect on the temperature history by including the porosity in the thermal conductivity model, while a further including of the mineralogy in the model gives minor effect on the estimated temperature history.

Case study 2 - Modelled versus measured thermal conductivities.

Case study 2 shows the temperature histories estimated by Models 3 and 4 (Table 1). Thermal conductivity are in both models estimated by the geometric mean model from the porosity and mineralogy (Figure 5). The differences lie in the determination of matrix conductivity, k_r . Matrix conductivity in Model 3 is determined from the TCD database of thermal conductivity measurements and mineralogy, while in Model 4 it is estimated by the geometric mean model from the mineralogy and the mineral conductivities shown in Table 3.

Using Model 3, the present day temperature profiles for the Permian is estimated about 70 K higher than that of Model 4. The present day temperature estimated by these two thermal conductivity models are shown in Figures 6 and 7. The oil window, (ca 100 -140 °C) predicted by Model 3 occurs in the Cretaceous section, while Model 4 predicted this temperature zone lays within the Jurassic section.

Model 3 is suggested to be more reliable than Model 4 since it depends on measurements of thermal conductivities. A decrease in the thermal conductivities determined by Model 3 is necessary to get

comparable temperature histories by these models. From the assumptions that there is a grain size effect on the thermal conductivity, and that the mineralogically based geometric mean model (Model 4) estimates too high thermal conductivities for the shale sections, the estimated thermal conductivities of Model 4 are corrected by a factor of 0.7 for the shale sections (Model 4a) (Figure 8). Usually is the ratio $k_{\text{shale}}/k_{\text{sandstone}}$ used in basin modelling programs in the range of 0.5 -0.7. A grain size factor of 0.7 is suggested, since these models is dependent of the mineralogy, and the lower thermal conductivity of shale sections is assumed to be partly due to a grain size effect and partly due to a mineralogical effect. The temperature histories estimated by this corrected version of Model 4 (Model 4a) are comparable with those estimated by the model based on measurements (Model 3). Model 4a gives a slightly higher present day temperature than Model 3 for the Jurassic and Tertiary, and a lower temperature for the Permian. The highest discrepancy (about 10 K) between these two models is for the Tertiary.

Including the mineralogical effect of using Model 4 instead of Model 3 in the Case study 1 with the two simplest models (Models 1 & 2) gives considerably lower temperatures in the sedimentary section (Figure 4). The mineralogy will in this comparison case be an important factor controlling the temperature history.

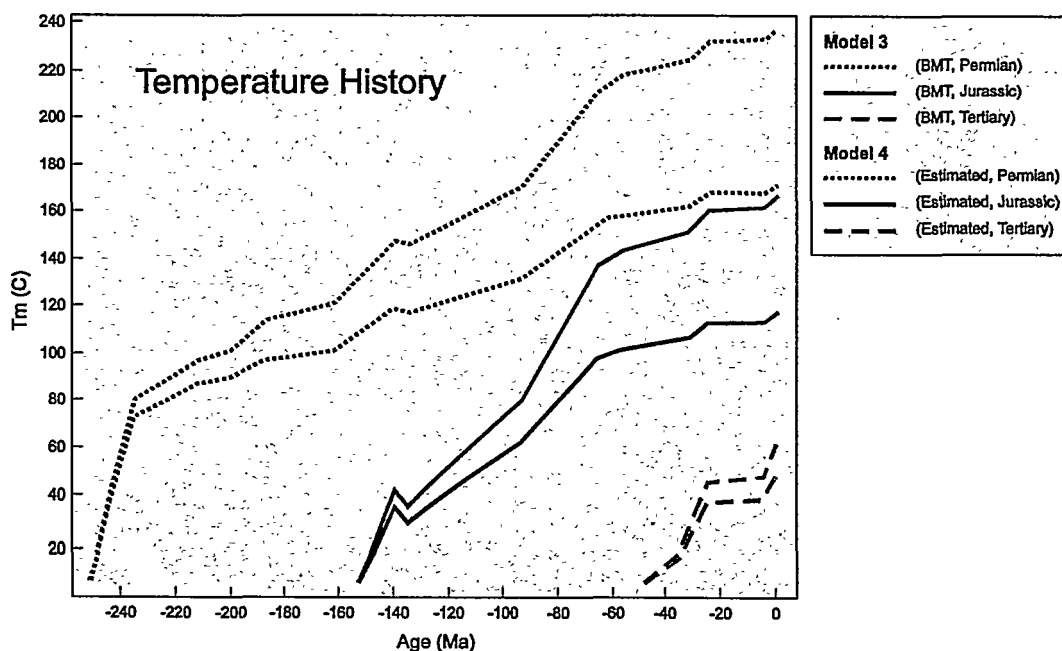


Figure 5. Case study 2. Temperature histories estimated by measured (Model 3) and estimated (Model 4) thermal conductivity models.

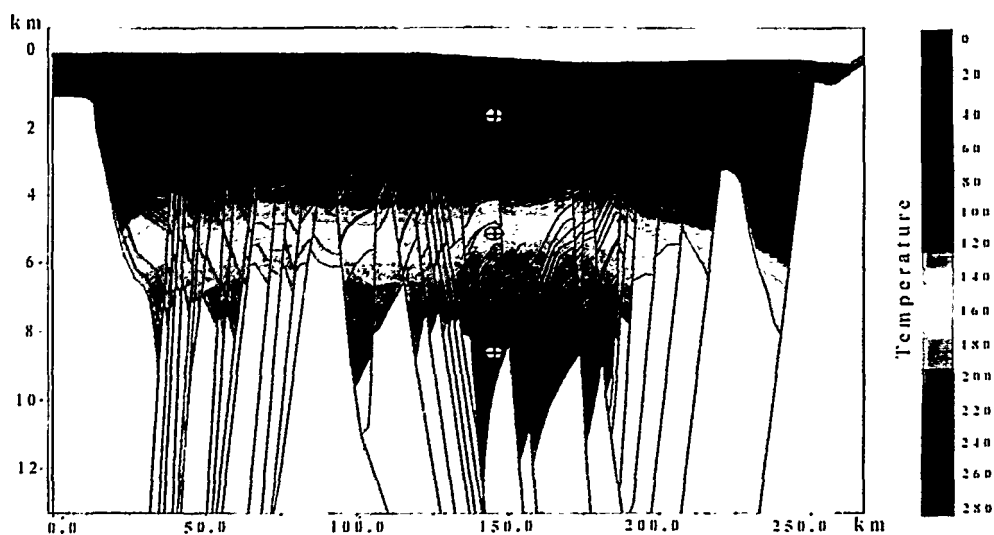


Figure 6. Present day temperature distribution ($^{\circ}\text{C}$) of the section estimated by Model 3.

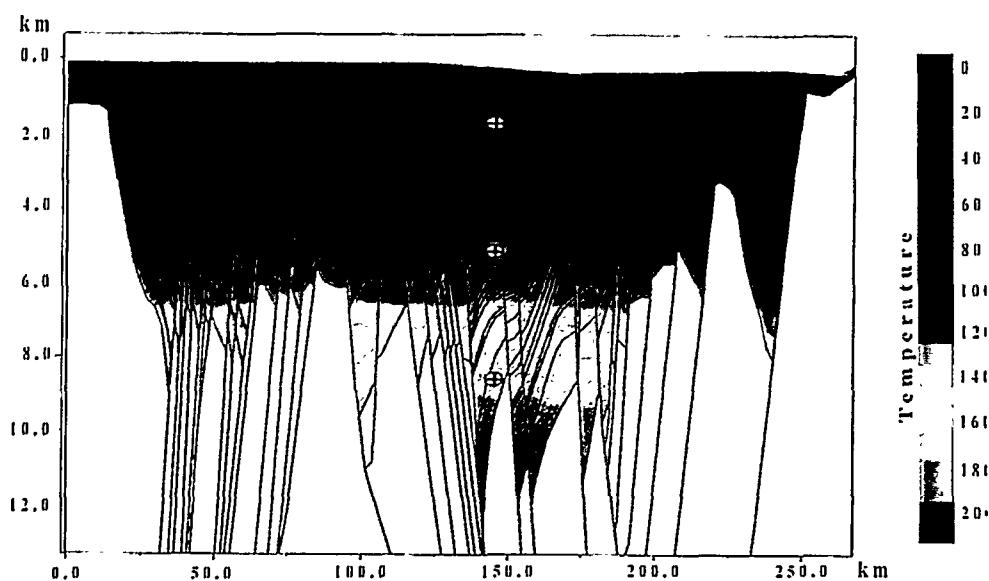


Figure 7. Present day temperature distribution ($^{\circ}\text{C}$) of the section estimated by Model 4.

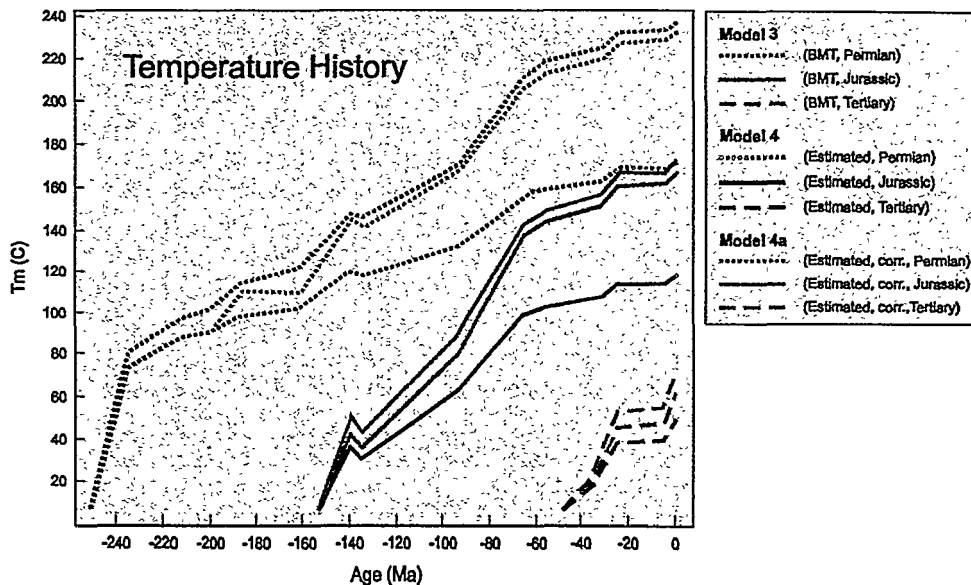


Figure 8. Case study 2. Temperature histories estimated by measured (Model 3) and estimated (Model 4) thermal conductivity models and a adjusted version of Model 4, where the shale sections are corrected for the grain size effect of the thermal conductivity (Model 4a).

Case study 3 - Comparison of the three mixing law models.

The consequences of the choice among the three mixing law models (Models 4, 5 & 6) are shown in Figure 9. The modelled present day temperature conditions within the Permian sediment sequence varies from 145 °C by using the arithmetic mean model to 230 °C using the harmonic mean model. In fact the temperature in the Jurassic sediment sequence when modelling with the harmonic mean model is higher than in the Permian using the arithmetic mean model. Figure 9 shows the importance of using the correct basic mean model since choosing less fitted model gives a rather biased temperature history.

In comparison with Model 3 in Case studies 1 and 2 where matrix conductivity is estimated from the TCD database by the BMT, the harmonic mean model (Model 6) are in best agreement with the temperature histories estimated by the BMT. Our experience with measuring and modelling thermal conductivities is that the arrangement of the fluid and matrix component due to the direction of heat flow has minor effect on the thermal conductivity (Midtømme & Roaldset, 1997a). From this reason we prefer the geometric mean model instead of the harmonic mean model.

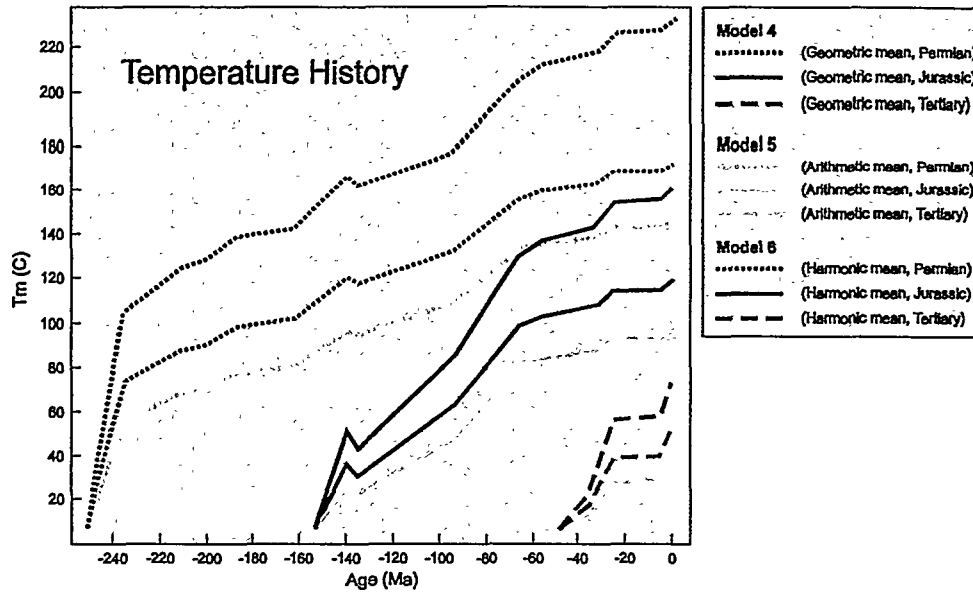


Figure 9. *Case study 3.* Temperature histories estimated by the three mixing law models; geometric (Model 4); arithmetic (Model 5) and harmonic (Model 6) mean models.

Case study 4 - The effect of varying the thermal conductivity of the Brent Group.

Thermal conductivity is in Figure 10 estimated by Model 3, the geometric mean model based on BMT database of thermal conductivity measurements and mineralogy. The differences in these three scenarios are in the thermal conductivity of Brent Group which is set as a constant: a) $k_{Brent} = 2.25$ W/m·K, which is approximately the mean thermal conductivity of this section estimated by Model 3; b) $k_{Brent} = 1.5$ W/m·K, and c) $k_{Brent} = 3.0$ W/m·K respectively. Because of the many coal beds in the Brent Group, this thermal conductivity is associated with more uncertainty than those of the other formations (Midttømme et al., 1996). The Brent Group along this cross-section is thinner than many of the other formations, and will certainly have less effect on the temperature history than the thicker formations.

The variation of thermal conductivity of the Brent Group has a small effect on the temperature history (Figure 10). Only for the Permian sediments is any discrepancy in the three temperature histories indicated. The largest discrepancy is 8 K between the scenario with highest and lowest thermal conductivity in the time period 100–160 Ma.

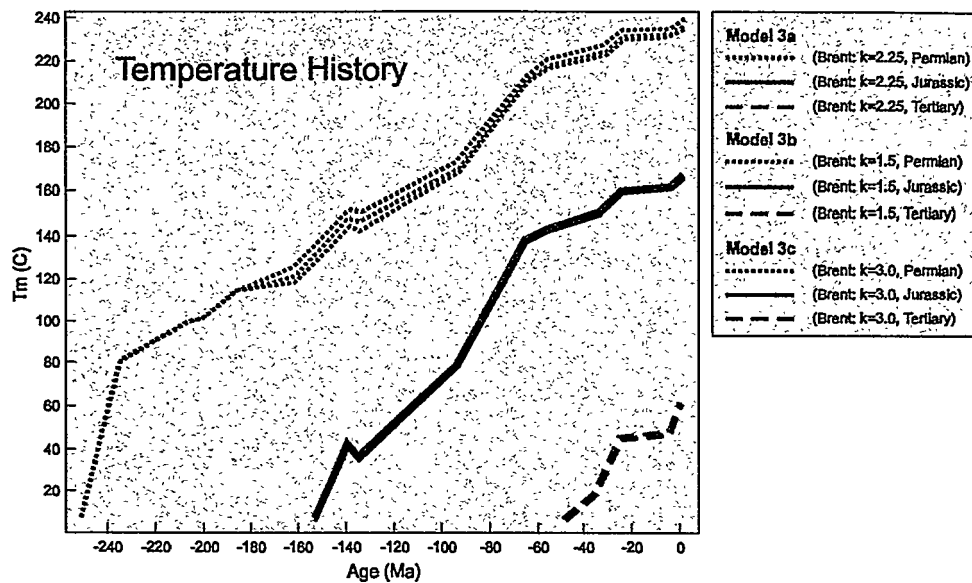


Figure 10. Case study 4. Temperature histories estimated with different thermal conductivities of the Brent Group.

CONCLUSION.

Considerable deviation in the estimated temperature histories is demonstrated by using different thermal conductivity models. Simplified models, which only take account of either the lithology (Model 1) or the lithology and porosity (Model 2), give a good estimate of the temperature history compared to more advanced models. The largest discrepancy in temperature histories appears in the mutual comparison between more advanced thermal conductivity models, which are based on mineralogy and porosity. Model 3 is suggested to be the most reliable model. In this model matrix conductivity, k , is based on a database of measured thermal conductivities (TCD) by the BMT programme. Model 3 gives considerably higher temperatures than Model 4 where matrix conductivity is estimated by the geometric mean model based on the mineralogy. A grain size correction of the geometric mean model (Model 4) of the shale units gives comparable thermal histories with the BMT model (Model 3). Using the three statistical mean models, respectively arithmetic mean, geometric mean and harmonic mean as basic model for estimating the thermal conductivity give very different temperature histories. Varying the thermal conductivity for the Brent Group has little effect on the modelled temperature histories.

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